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Structural Ultracapacitors: Development and Performance

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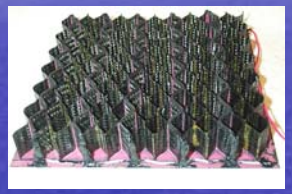
Boundless Corporation

Boundless Focuses on Advanced Electrochemical Technologies

Structural Energy Storage - lithium-ion batteries, ultracapacitors



Materials - high porosity separator, nanowire li-ion battery cathode, composite grid for PbA

Integrated Systems - li-ion EV packs, HEV buses, charge control

Consultation and Test

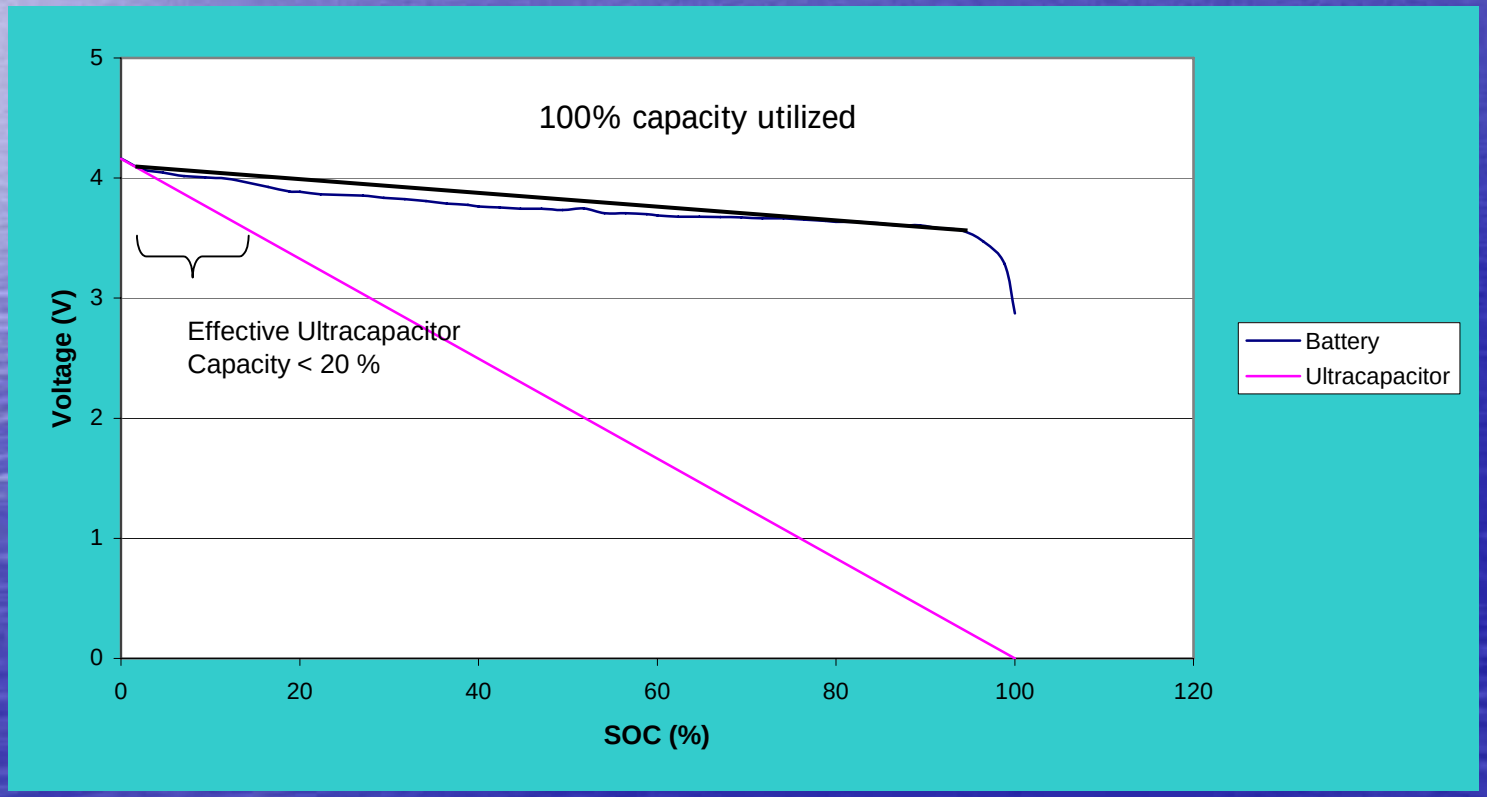
OUTLINE

- Ultracapacitors - Introduction
- Structural Energy Storage
- Structural Ultracapacitors Design and Performance
- Application Modeling, Performance and Thermal
- Conclusions

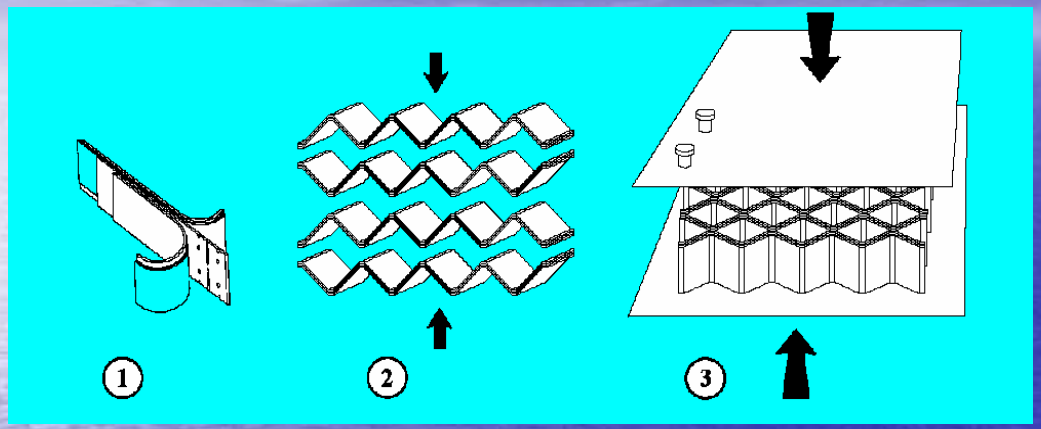
Ultracapacitors Span the Power/Capacity Performance of Batteries and Capacitors

- Ultracapacitors aka Supercapacitors, double-layer capacitors, electrochemical capacitors
- Higher power than batteries, higher capacity than capacitors
- Charge Capacity (A*s) = Q = Farad * Voltage = Ah * 3600
- Energy Capacity (W*s) = J = 1/2 * Farad * Voltage^2 = Wh *3600
- Aqueous Electrolyte = 1 V; Organic Electrolyte = 2.5 V so for equivalent capacitance organic > 6 x energy storage
- Current/voltage curve not matched well to batteries

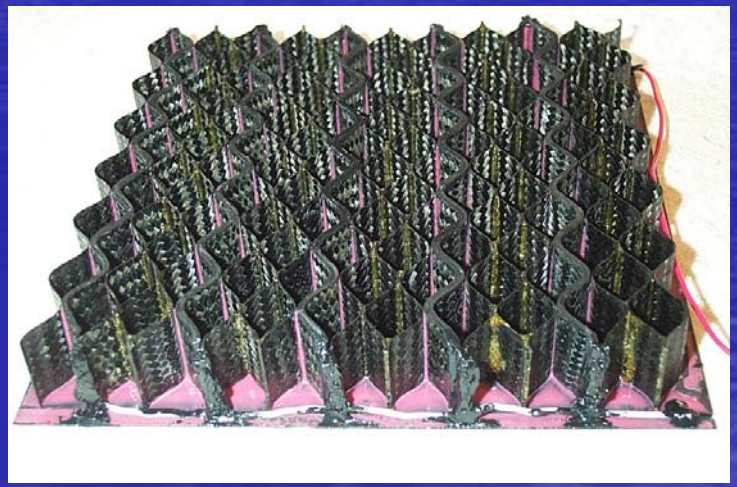
Hybrid Power Systems Benefit from Electronic Management



What is Structural Energy Storage?



- Build elongated electrode cells
- Corrugate into honeycomb core
- Attach interconnects and bond face sheets
- U.S. Patent #5,567,544 & 5,793,603



Multifunctionality Increases Specific Energy & Power, Energy & Power Density

Effective Specific Energy or Power increases because electroactive materials replace inert structural components:

ESE (Wh/kg) = Wh / (MFBP (kg) – replaced inert core (kg))

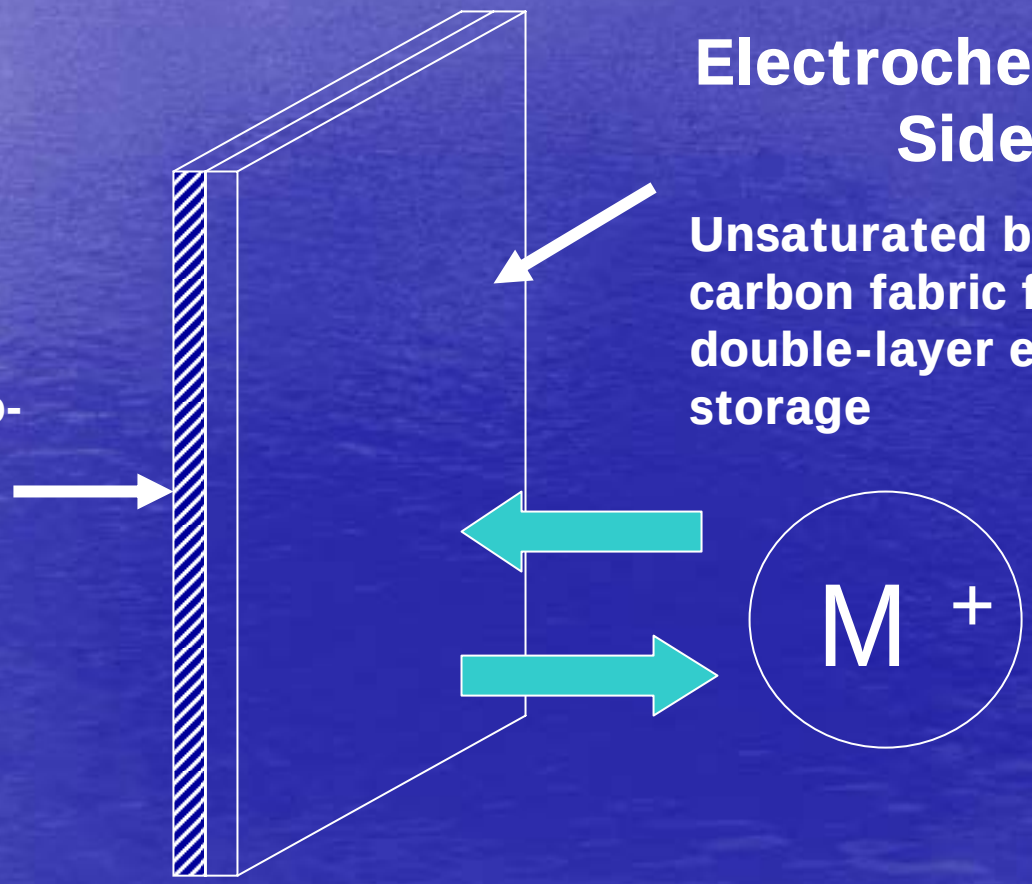
- Effective battery volume goes to zero – effective energy …density and effective power density become infinite
- Structure must be incorporated into materials to obtain net mass benefit
- Expected improvements 20 - 30 %, primarily from secondary mass

Partially Saturated Carbon Fabrics Have Dual Functionality

Structural Side

Fully saturated with thermoset or thermo-plastic resin for:

- Strength
- Seal
- Current collector



Electrochemistry Side

Unsaturated bare carbon fabric for double-layer energy storage

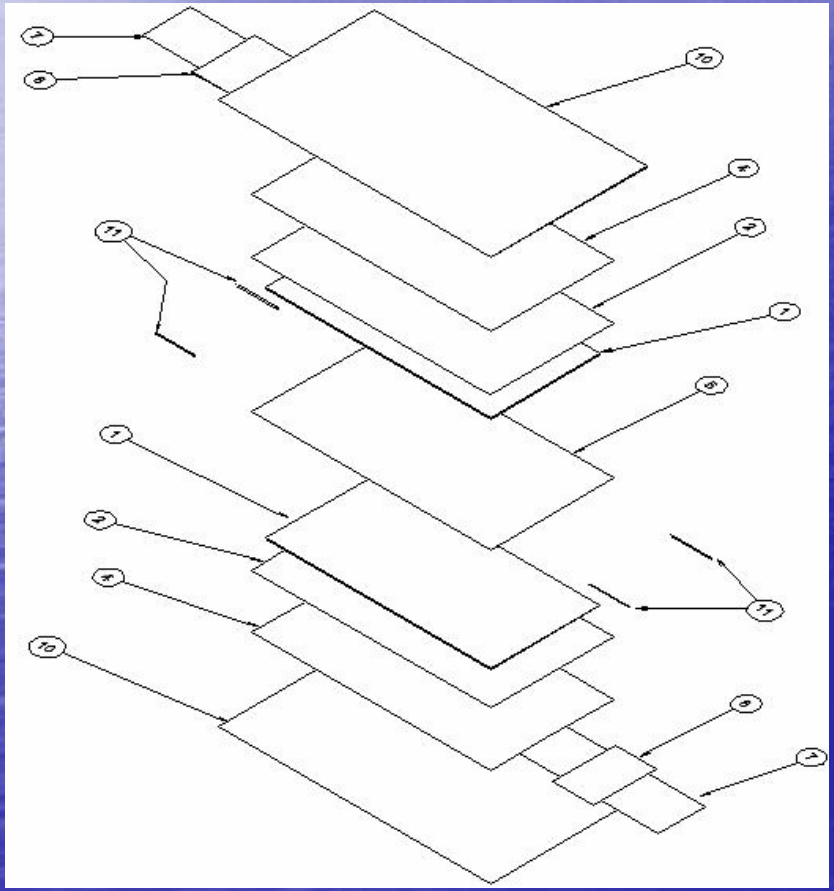
Structural Electrode - High Surface Area Carbon Fabric Composite

- Baseline of carbon fabrics, PAN & Pitch
- Incorporate activated carbon powders into partially saturated electrode
- Partially saturated activated carbon fabrics
- Activate partially saturated carbon fabrics
- Dual fabric - partially saturated carbon fabric (~90%) with activated carbon fabric on surface

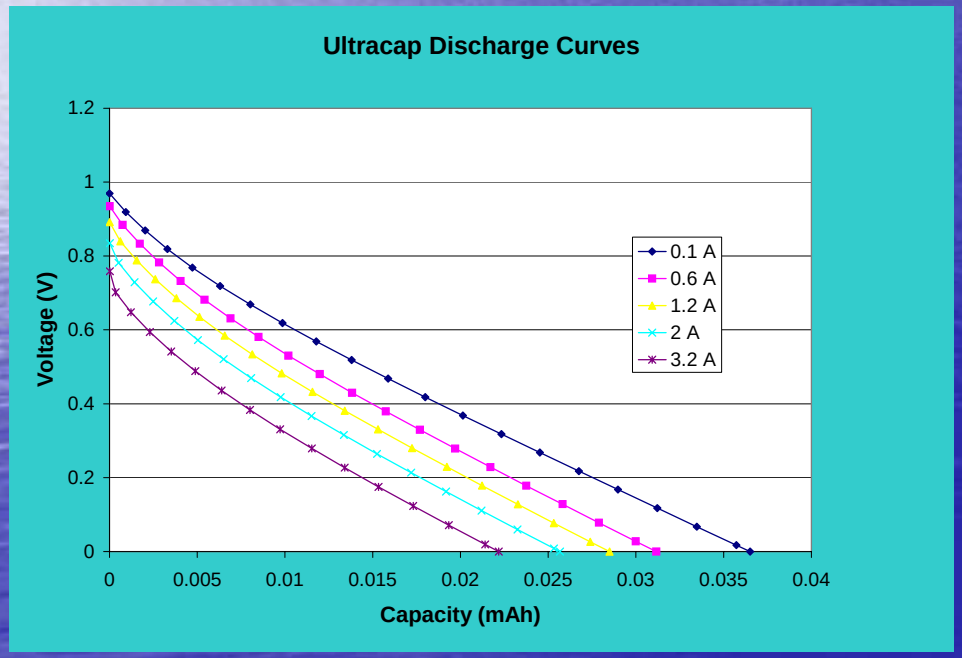
Materials Evaluations Considered Performance, Stability and Strength

- Variety of activated carbons evaluated
  - High surface area fabrics had higher capacitance
  - Lower surface area fabrics had better resistance
  - Higher surface area fabrics more costly
- Partially saturated carbon fabrics optimized for strength and resistance
- Aqueous electrolytes chosen for low resistance
- Matrix resins selected for high strength and compatibility with electrolyte
- Current collectors selected based on compatibility with electrolyte
- Seals obtained with laminate packaging
- Compression provided external to cell

Stack Up is Symmetric



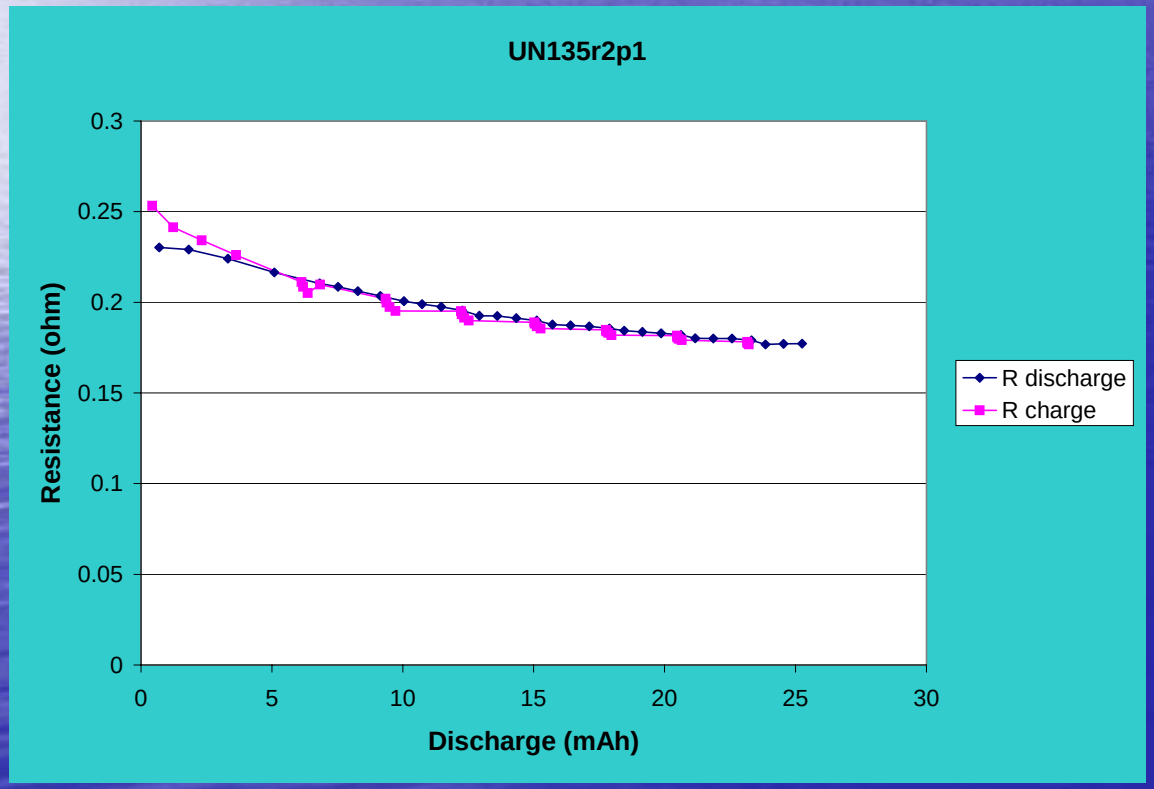
Ultracap Charge Capacities are About 4% Those of Lithium-Ion Batteries



..but energy storage is closer to 0.6 %

A	Crate	mAh	mWh	Wh/kg	Wh/l
0.1	3	36.5	18.3	0.93	1.6
0.6	16	31.2	15.6	0.80	1.4
1.2	33	28.5	14.3	0.73	1.3
2	55	25.6	12.8	0.65	1.1
3.2	88	22.2	11.1	0.57	1.0

Power Profile versus SOC Slopes Downward



$Pmax = Voc^2 / 4R$

5.68 W

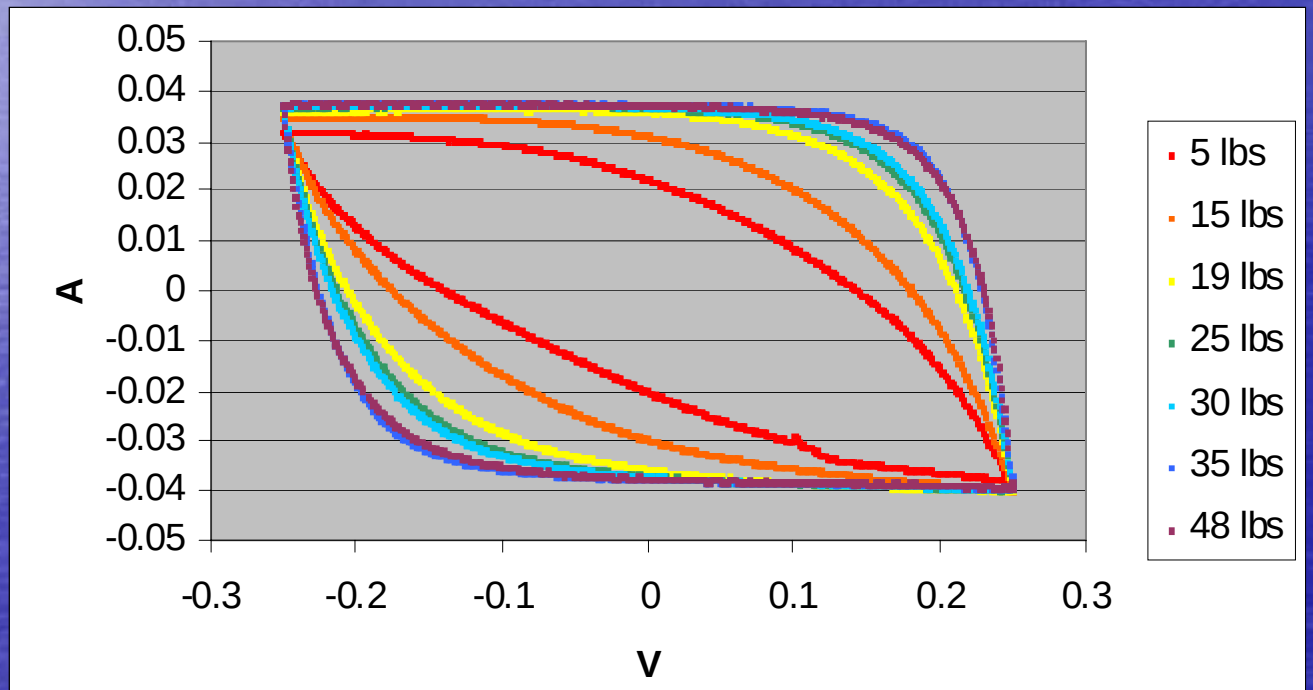
11.3 A

310 C

290 kW/kg

500 kW/l

Cell Compression was Found to be Important



Scanning with more external pressure improved the performance

Models Developed to Understand Hybrid Performance

- Used power test data for batteries - Resistances and OCV vs SOC
- Used Puekert data for Ultracapacitors - Fit capacity to SOC vs rate with 2nd order polynomials
- Solutions iteratively fit so both ultracaps and batteries had same voltage
- All constant current discharges
- Could solve for either ultracaps, batteries or together
- Time of discharge could be varied

Parallel Connections Demonstrated Significant Participation of Ultracapacitors

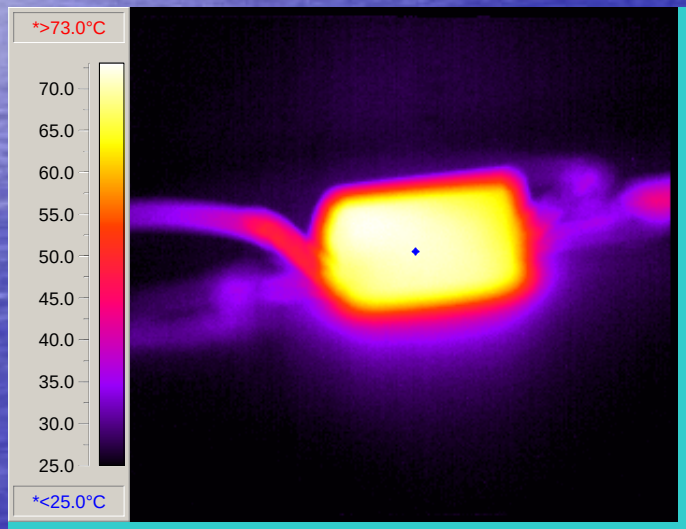
	Bat only	U only	Together
1 s	24	140	164
10 s	19	73	91
60 s	11	23	33

(all values in A)

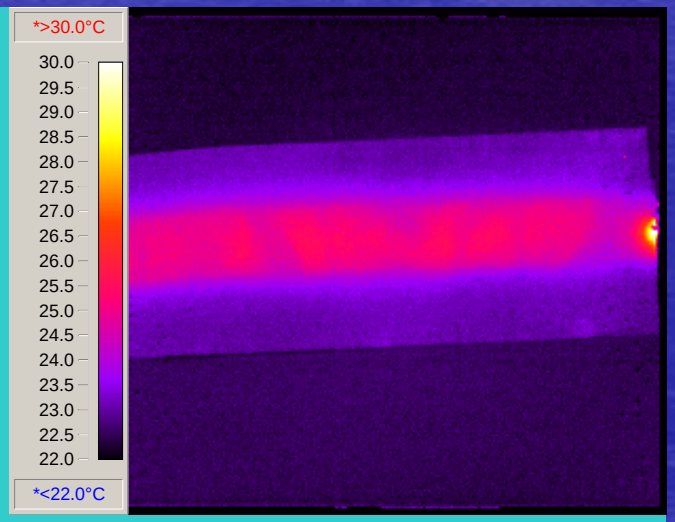
Model used to evaluate combinations of structural ultracapacitors and structural batteries

Distributed Energy Storage has Thermal Management Implications

Higher surface area aids conductive heat transfer - important for high power applications

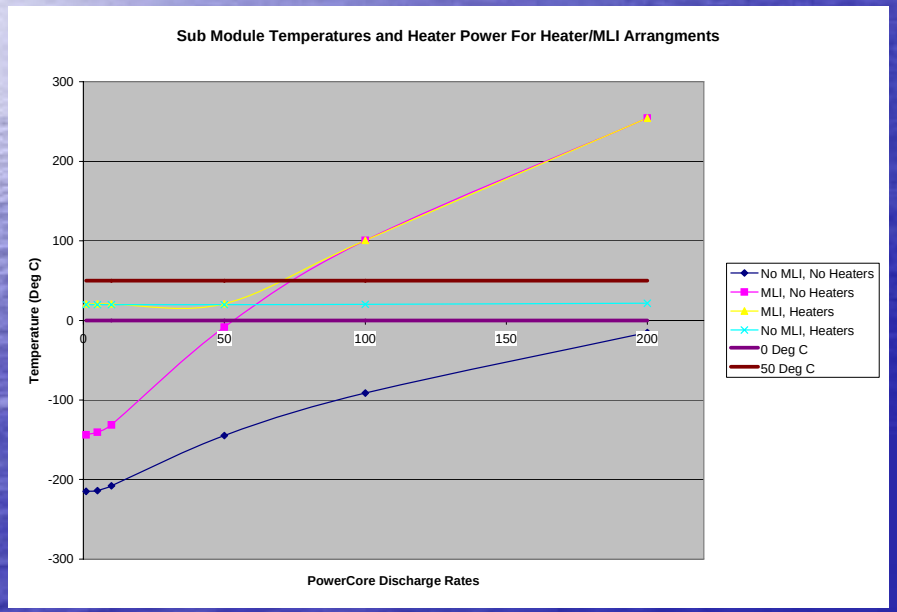


> 65° C



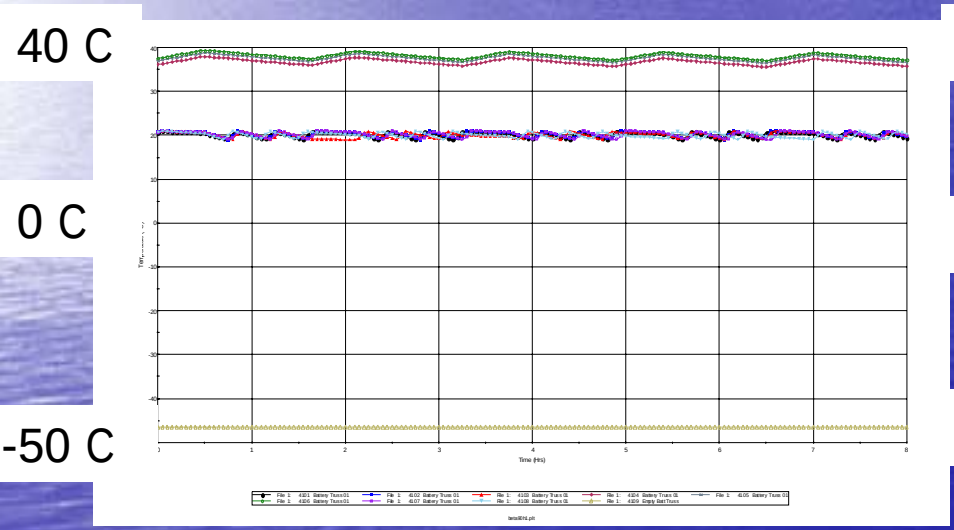
< 28° C

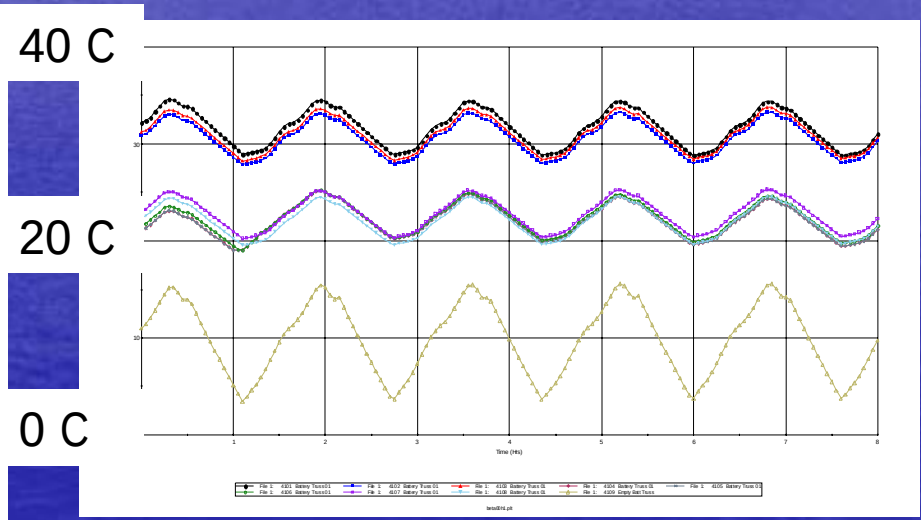
Thermal Management a Challenge for Spacecraft with Exposed, Extended Arrays



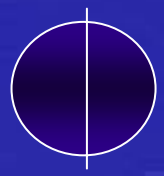
- Thermal model created to evaluate specific application
- General information obtained - more detailed scenario and model required
- Heaters and insulation required
- High power operation is also limited

Shading Causes Localized Thermal Imbalance for Either LEO Beta Angle





Beta 90



Beta 0

Both assume discharge at 5 C rate in sun (hot case)

Average Heater Power Depends on MLI Emissivity, Rate and Orbit

Orbit	C-rate	Heater (W)	Heater (W)	Heater (W)
Beta 0	1	1.64 (0.05)	0.86 (0.025)	0.52 (0.015)
	5	0.7		
	10	0.08		
Beta 90	1	2.54		
	5	1.97		
	10	0.3		
MLI emissivity in ()				

- Heater requirements (per 10 Ah cell) are <10% of energy capacity
- Specific heater power for cells have greater variance and might require active cell balancing
- Thermal management solutions will likely require design for actual discharge rates and MLI will be used depending on spacecraft orientation

CONCLUSIONS

Structural energy storage require dual functional cell components to realize optimized performance

Structural ultracapacitors developed using activated and non-activated carbon fabrics

Modeling demonstrates significant impact of ultracapacitor/battery hybrid even without electronic management

Thermal management will require creative solutions specific for different applications - but appear feasible

THANK YOU!