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Office of Energy Efficiency & Renewable Energy
Innovation for Our Energy Future

Ultracapacitor Applications and Evaluation for Hybrid Electric Vehicles

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Presented at the 7th Annual Advanced Capacitor World Summit Conference

NREL/PR-540-45596

Discussion Points

- Discussion of batteries vs. ultracapacitors for advanced vehicles
- Simulation results of HEV fuel economy impact from reducing the storage system's energy window
- 15%-30% HEV fuel economy improvements with 50-100 Wh ultracapacitors
- Evaluation of lithium ion capacitors for HEV applications
- Thermal evaluation of a high-voltage ultracapacitor module for start-stop applications

Strengths and Weaknesses of Ultracapacitors

Strong Attributes of Ultracapacitors	Potential Specific Use
High specific power and efficiency	Engine assist
Efficient and fast charge acceptance	Regen capture
Low resistance	Lower cooling needs (less expensive)
Quick response (short time constant)	Supporting engine transients
Long anticipated calendar and cycle life	Fewer replacements (less expensive)
High specific power at low temperatures (cold starts)	Smaller size and less expensive

Weak Attributes of Ultracapacitors	Specific Use
Low specific energy	Limited "durations" for power draw
High self-discharge	Loss of functionality and balance at start
Quick voltage variation	More difficult to control
Low energy density	Limited time for running auxiliaries at idle
High cost per unit energy	Too expensive currently

The best use for Ucaps are strategies that make engines operate more efficiently (idle off, load leveling), frequent use capturing regen energy, and start-stop.

A Couple of Thoughts

- Taking advantage of an ultracapacitor's strengths while minimizing the impact of its weaknesses to make its "value" competitive with batteries
- It should be for a specific application to show "value" in terms of "life-cycle cost"
  - Fuel economy
  - Replacement cost
  - Life
  - Durability and reliability
  - Quality
  - Functionality

Ucap Is Energy Limited!
How Much Energy Is Needed for Various Events?

Event	How Much Energy Needed
Assist:20/30 kW constant power for 15/10 s	83.3 Wh
Accessory: 3 kW constant draw for 1 minute	50
Accessory: 1 kW constant draw for 1 minute	16.7
2% Grade going 35 mph for 1 minute Ŧ	70 Wh
4% Grade going 35 mph for 1 minute Ŧ	170 Wh
US06 Driving Cycle *	155 Wh
UDDS Driving Cycle *	80 Wh

Ŧ Note: Engine provides propulsion up a grade, the estimate is for capturing regen to hold a 1520 kg vehicle speed going down a grade.

•Total Energy (at wheels) calculated for 1520 kg vehicle (regen); 50% of energy in the cycle's largest deceleration event

Cold-start capability is expected to dictate the size of batteries, but not the case for Ucap.

Prius has a 1.4 kWh NiMH battery but capacity is for life margin and warranty.

Vue mild hybrid has a 0.6 kWh NiMH battery.

Potential Use of Ultracapacitors in Light-Duty Electric-Drive Vehicles

Micro Hybrids (12 V-42 V: Start-Stop, Launch Assist) 	**NiMH and Li-ion: Yes** **Ucap: Likely** **Ucap + VRLA: Possible**	**Min energy needed** **15-25 Wh**
Mild Hybrids (42 V-150 V: Micro HEV Function + Regen)  	**NiMH and Li-ion: Yes** **Ucaps: Likely if engine is not downsized** **Ucaps + VRLA: Possible**	**25-70 Wh**
Full Hybrids (150 V-350 V: Power Assist HEV)  	**NiMH and Li-ion: Yes** **Ucaps: Possible** **Ucaps + (NiMH or Li-Ion): Possible**	**60-150 Wh**
Fuel Cell Hybrids  	**NiMH and Li-ion: Yes** **Ucaps: Likely if Fuel Cell is not downsized** **Ucaps + (NiMH or Li-Ion): Possible**	**60-150 Wh**
Plug-in HEV (EV)  	**Li-ion: Yes** **Ucaps + high energy Li-ion : Possible**	**5-20 kWh** **(50-90 Wh*)**

* Energy for a Ucap in combination withLi-Ion

Analyzing the Impact of Energy Window on Power-Assist HEVs

- **Motivation:** Investigate the relation between in-use energy window and fuel economy (a request from USABC/FreedomCAR)
- **Approach:** Simulate a midsize sedan with different component power levels and control settings for different drive cycles using PSAT

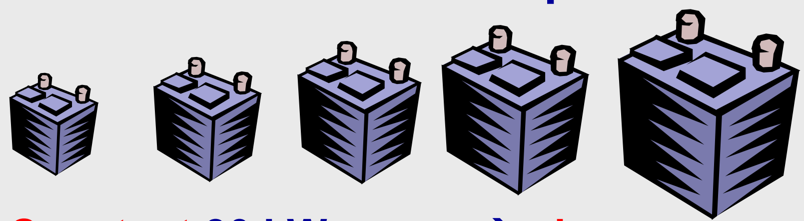
Midsize Car Assumptions

FA = 2.27 m^2
CD = 0.30
Crr1 = 0.008
Crr2 = 0.00012

Mass = 1675 kg
Engine = 90 kW
RESS/Motor = 30 kW
Elec accessories = 500 W
Mech accessories = 230 W

Simulated different ES energy content cases with the otherwise constant platform values

Smallest ES energy



Largest ES energy

Constant 30 kW power → changing P/E ratio

Constant SOC-based controls (charge sustaining)

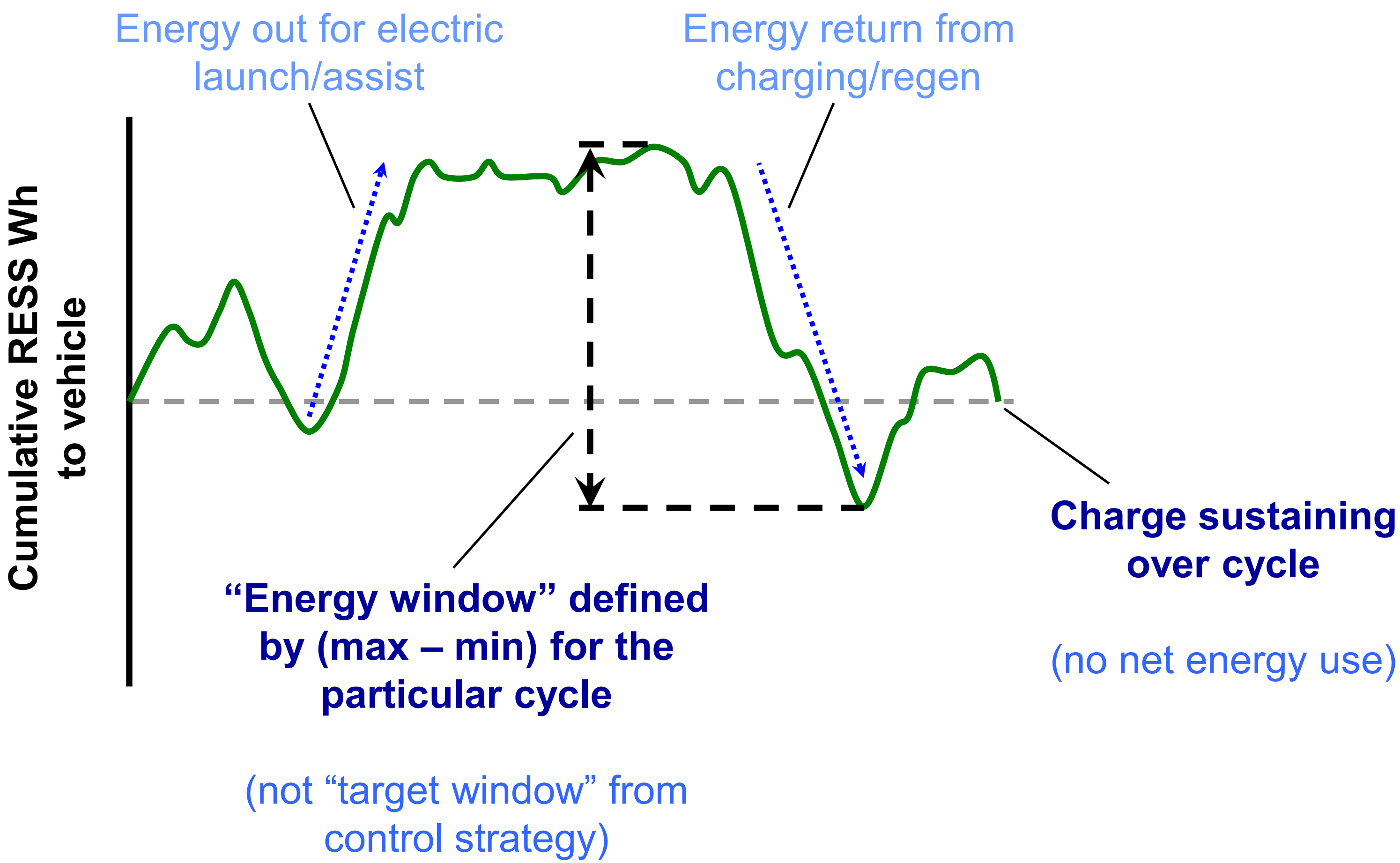
↓

Changing Wh control window tolerance

Source: J. Gonder, Presentation to USABC, July 19, 2007

Definition of ES Energy Window Use (for a drive cycle or event)

RESS use indicated by slope of energy line

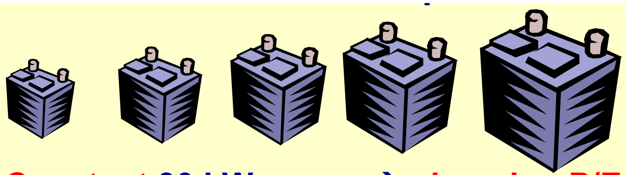


Energy Window Used ≤ Available Energy

Source: J. Gonder, Presentation to USABC, July 19, 2007

Three Cycles Simulated to Observe Energy Window and Fuel Use

Smallest ES energy



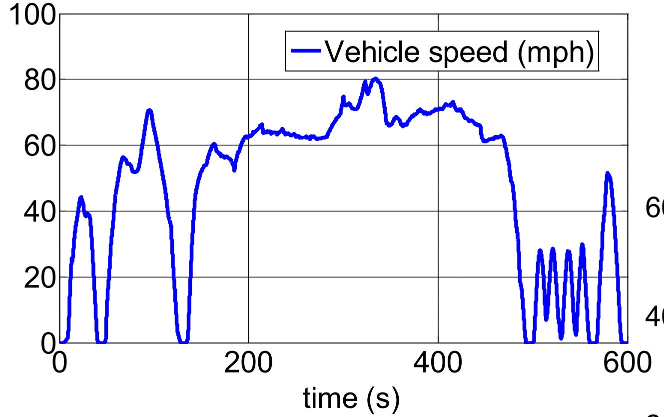
Largest ES energy

Constant 30 kW power → changing P/E ratio

Aggressive driving

US06 Cycle

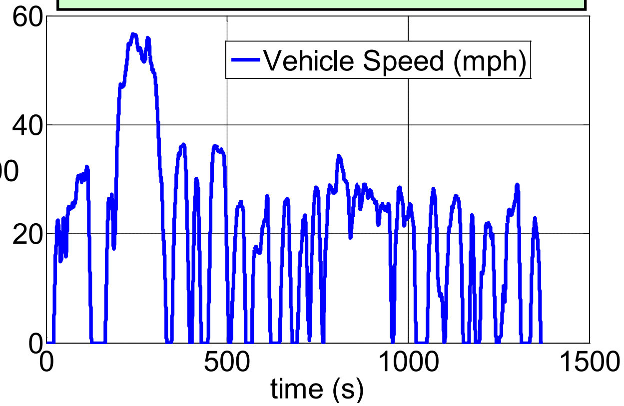
- Mean power during:
  - Propulsion = **21 kW**
  - Deceleration = **-17 kW**
- No grade



Mild urban driving

UDDS Cycle

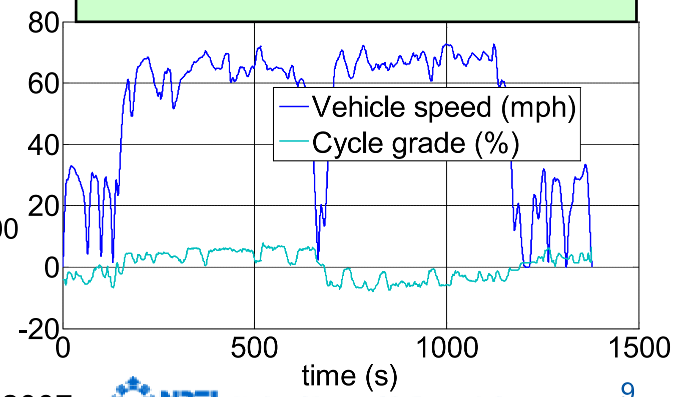
- Mean power during:
  - Propulsion = **7 kW**
  - Deceleration = **-5 kW**
- No grade



Up and down, foothills driving

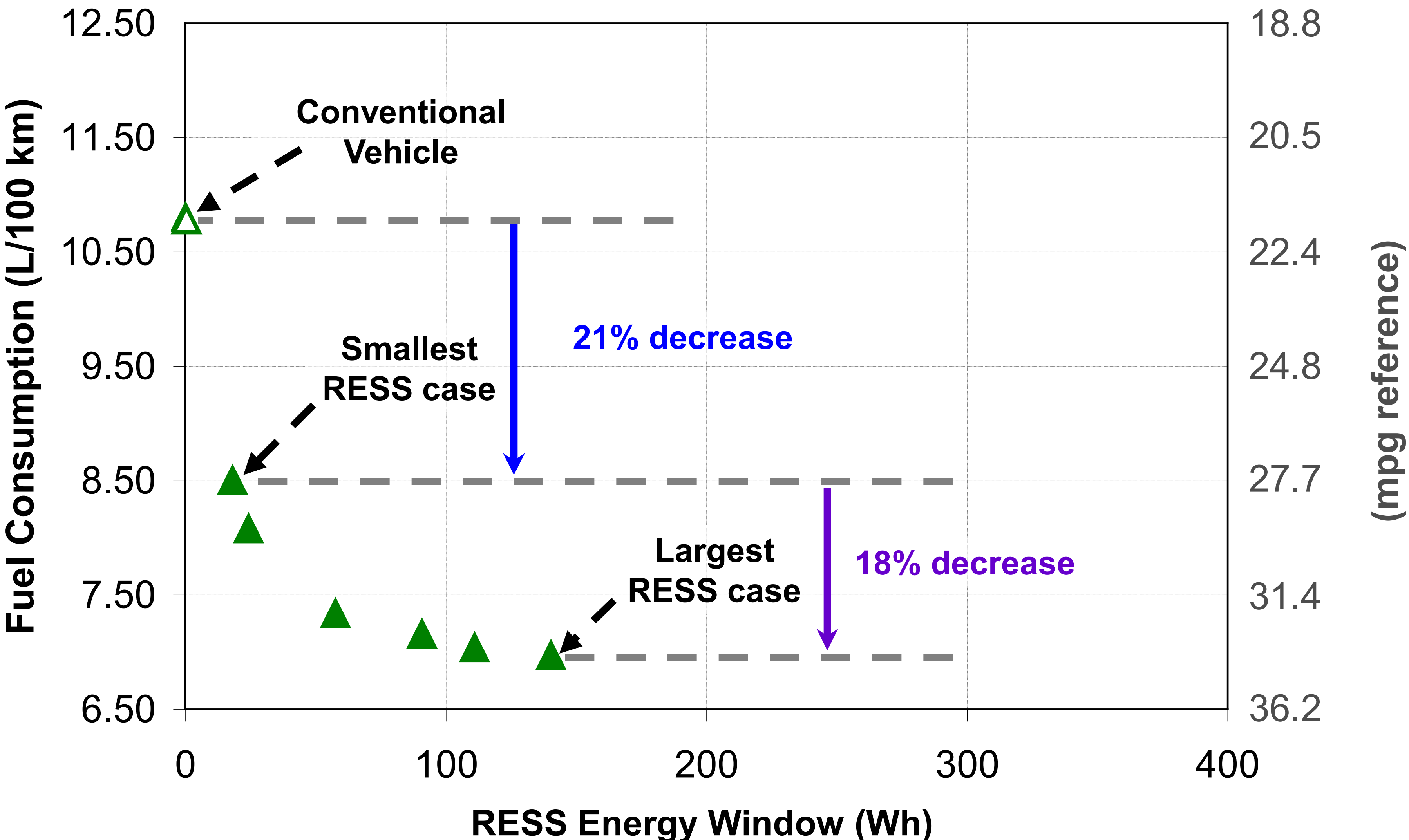
“NREL to Genesee Cycle”

- Mean power during:
  - Propulsion = **23 kW**
  - Deceleration = **-12 kW**
- Considerable grade



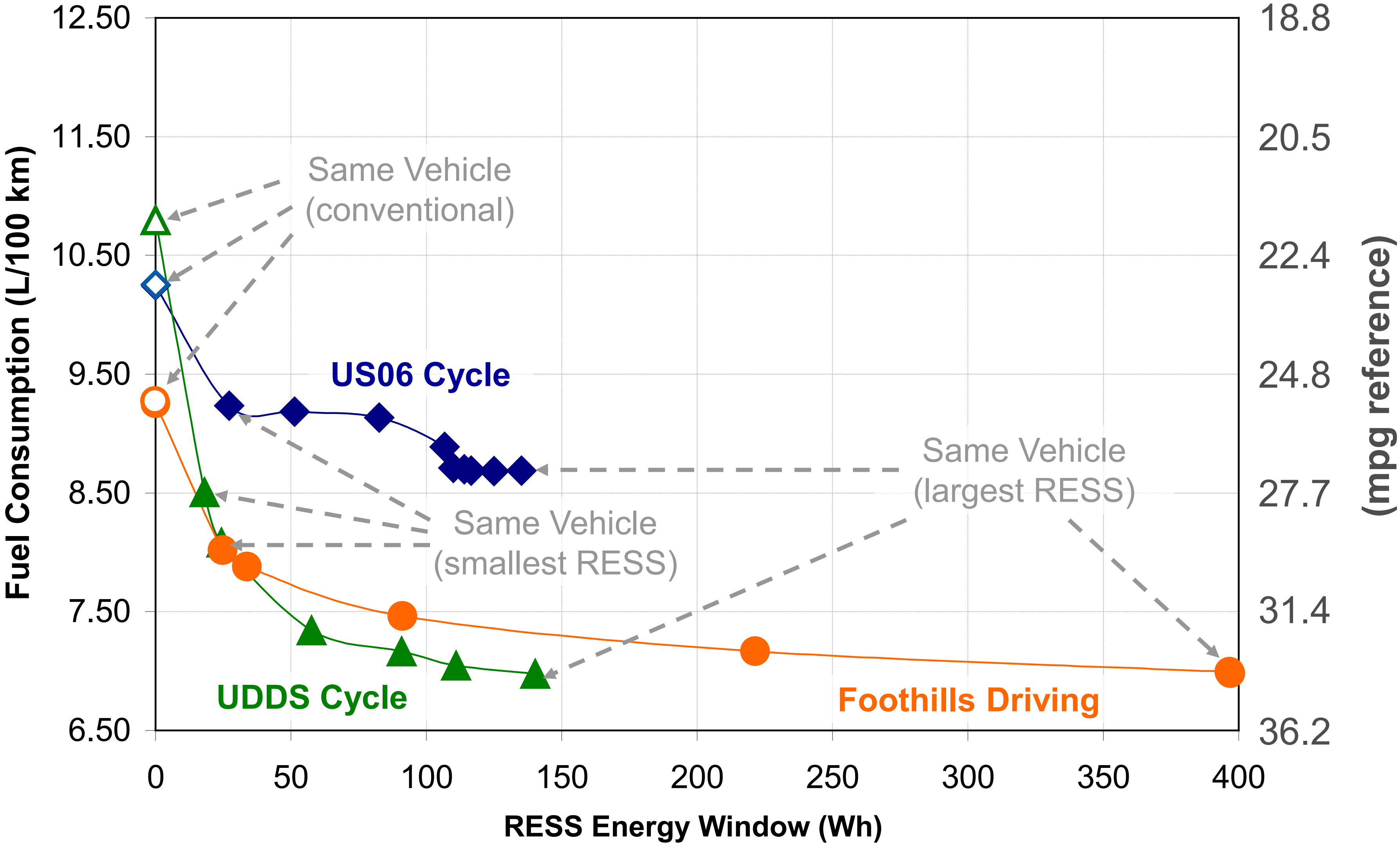
Source: J. Gonder, Presentation to USABC, July 19, 2007

On City Cycle (UDDS), Large Fuel Savings Result from Hybridization



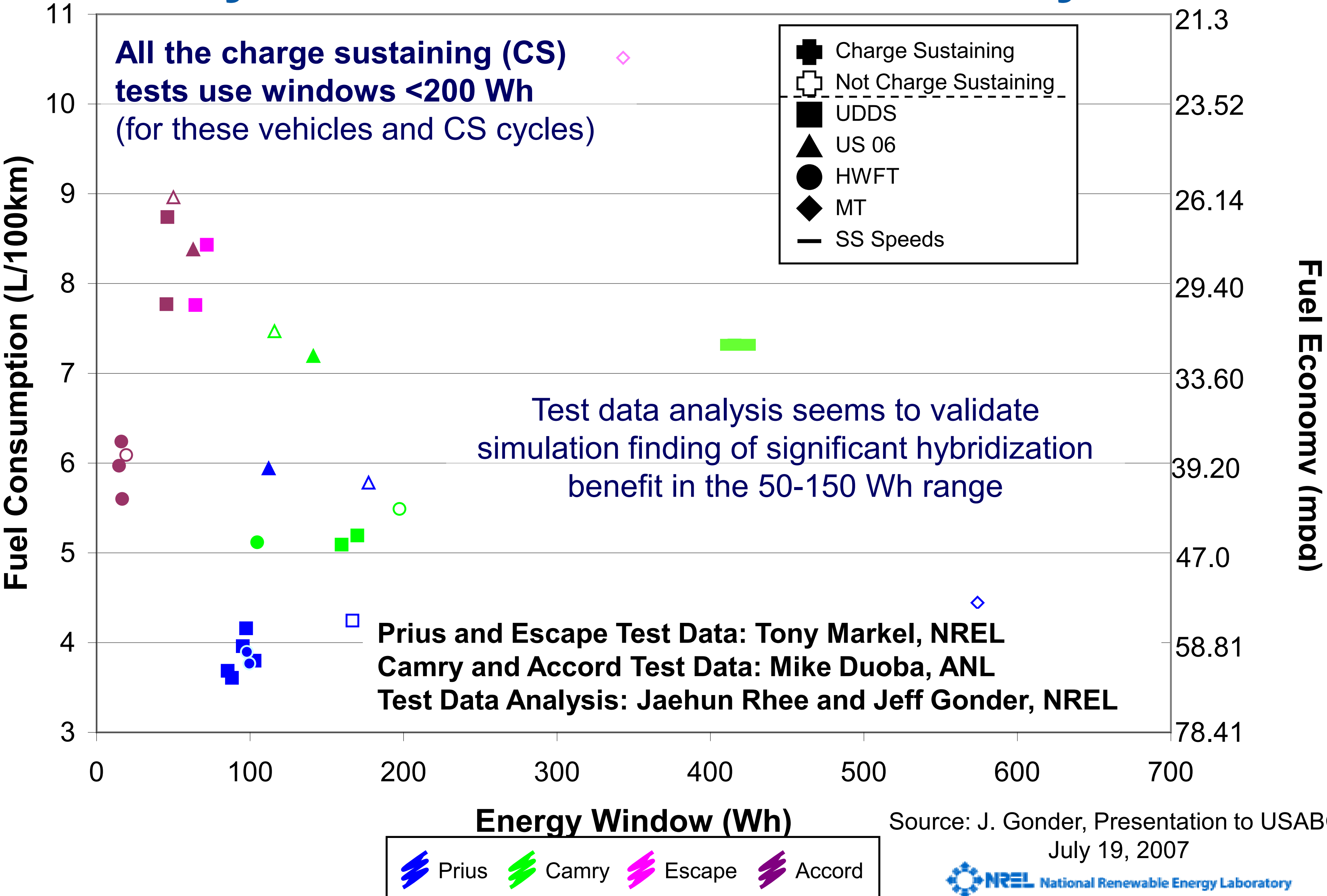
Source: J. Gonder, Presentation to USABC, July 19, 2007

Summary Results of ES Energy Window and Fuel Economy Simulations



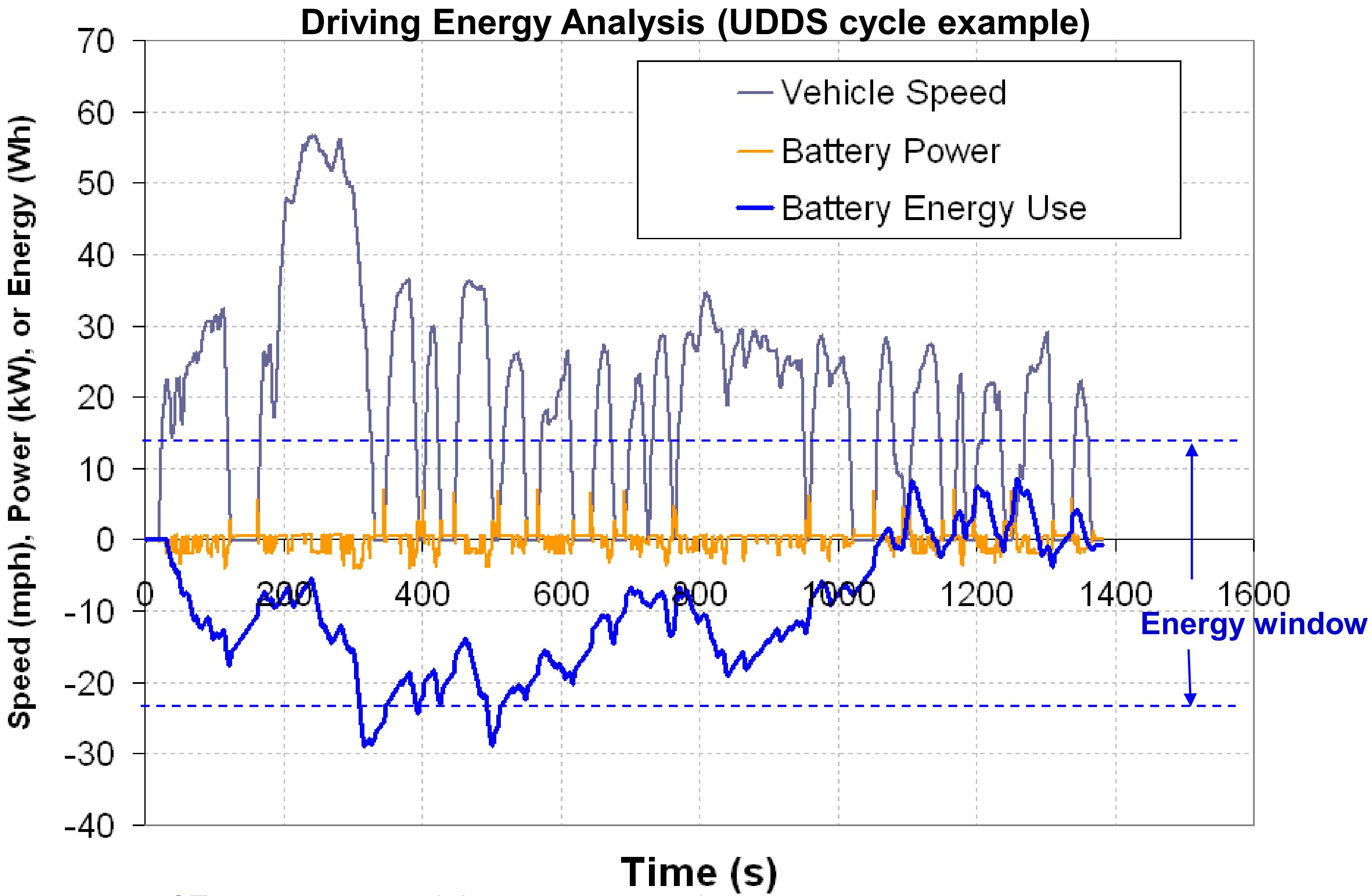
Source: J. Gonder, Presentation to USABC, July 19, 2007

Vehicle Test Results: Battery Energy Use for Today's HEVs under Various Drive Cycles



Source: J. Gonder, Presentation to USABC, July 19, 2007

2007 Mild Hybrid Dyno Data* Analysis Indicates <50 Wh Energy Use for Typical Driving—Already Reasonable Ucap Range



* Department of Energy-sponsored dynamometer testing

Mild and Power-Assist Hybrids with Ucaps

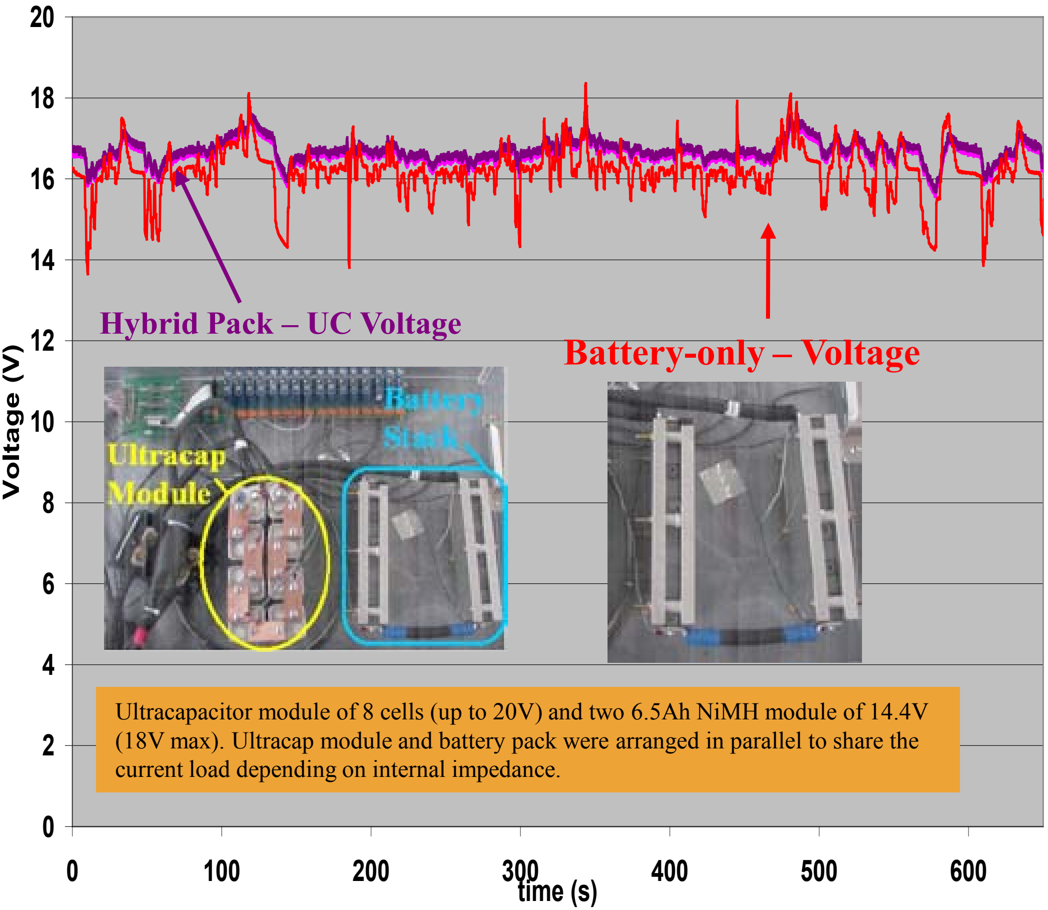
- It is possible to use ultracapacitors (with available energy of 50-150 Wh) in power-assist HEVs with modest fuel economy improvements
  — However, acceleration and passing on grade performance considerations could be limiting factors
- 15%-30% HEV fuel economy improvements with 50-100 Wh ultracapacitors
- A project is underway on a vehicle to demonstrate Ucaps in mild hybrids
  — To be discussed in future meetings

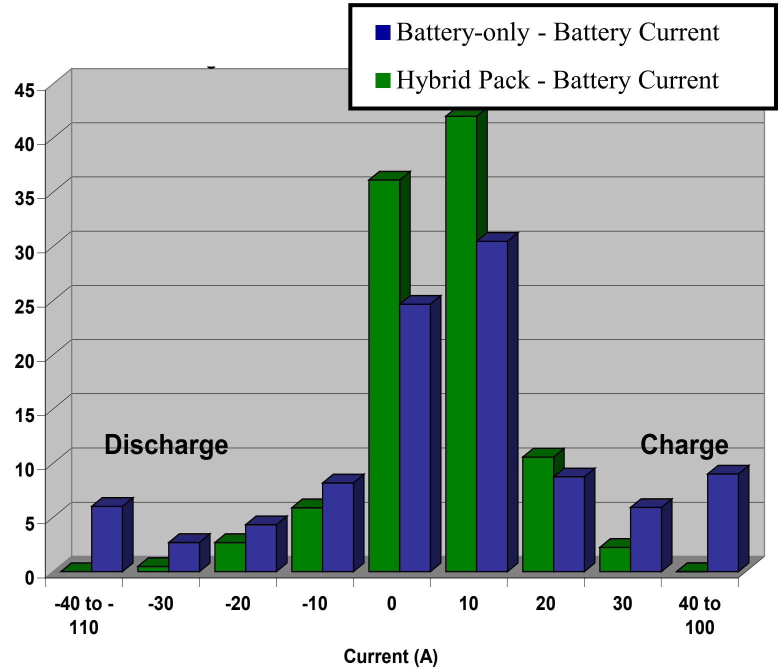
Previous NREL Tests Have Shown That Combining Ultracapacitors Filters High Current Transients In Batteries

Source: M. Zolot (NREL Reports and 2003 Florida Capacitor Seminar)

Parallel connection; no DC/DC converter

May not be practical to implement in vehicles.





- Overall, batteries in the hybrid pack experienced no currents larger than ±40 A, while the batteries in traditional pack saw currents up to ±110 A.
- Up to 33% narrower battery SOC cycling range was observed in hybrid pack; this has the potential to increase battery life.

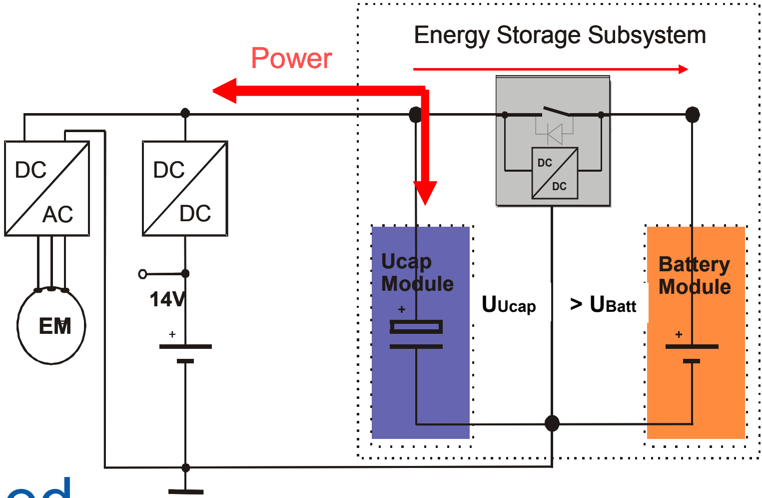
Advantages/Disadvantages of Hybridizing Energy Storage (Ucap + Battery)

Advantages

- Reduced battery currents
- Reduced battery cycling range
- Increased battery cycle/calendar life (to what extent?)
- Increased combined power and energy capabilities
- Lower cooling requirements
- Better low-temperature performance

Disadvantages

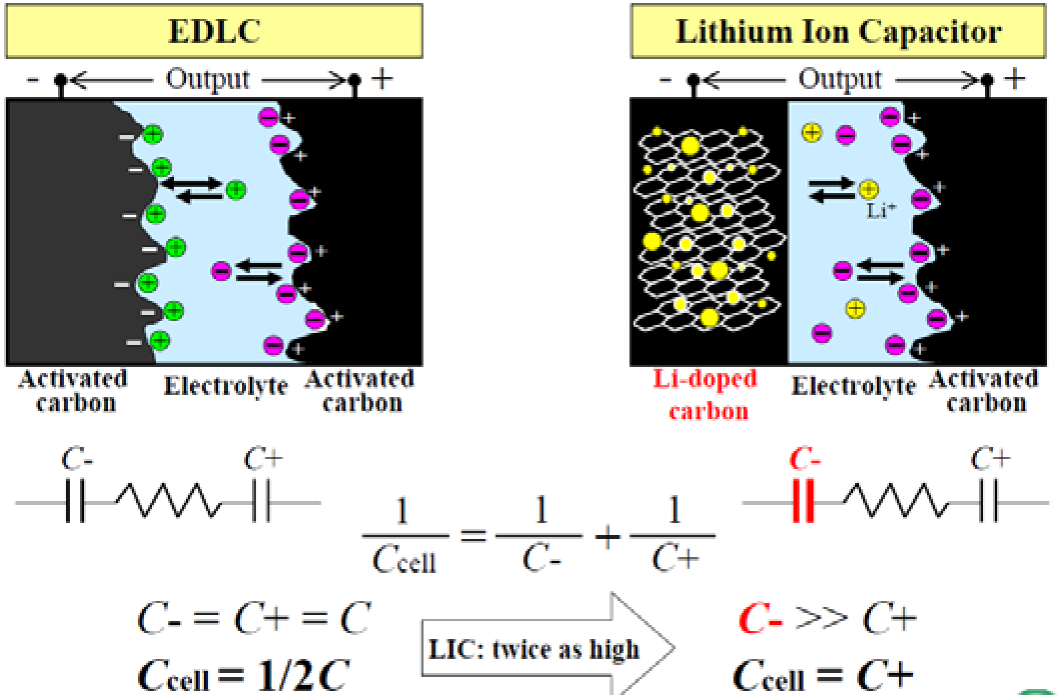
- Complex control strategy
- Larger volume & mass
- Need for electronics for each system
- Increased energy storage cost
- Unknown side effects if directly coupled
- Any need for DC/DC converters adds even more cost and complexity



Source: Continental ISAD, "New Energy Storage Concept," Proceedings of AABC-04

Thermal/Electrical Characterization of JSR Micro Lithium Ion Capacitor (LIC)

- JSR Micro contacted us to express interest in thermal characterization of their asymmetric capacitor

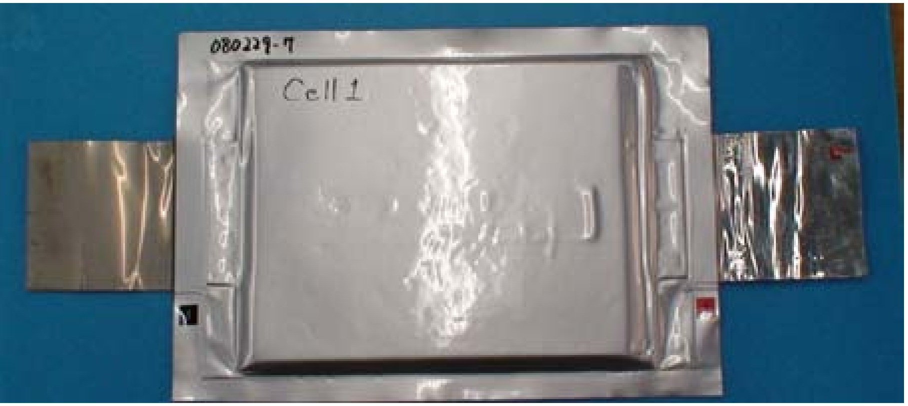


Source: www.jmenergy.co.jp/en/product.html

- JSR Micro claimed higher energy than C-C Ucaps with the same power capability
- We received 3 cells for characterization per USABC protocols

JSR Micro LIC Cell Characteristics

Cell Number (#)	Mass (kg)	Voltage (Volts)	Dimensions (inches)	Impedance (mOhms)
Cell 1	0.205	2.669	5.5" x 4" x 0.330"	1.58
Cell 2	0.205	2.669	5.5" x 4" x 0.330"	1.62
Cell 3	0.205	2.672	5.5" x 4" x 0.330"	1.6

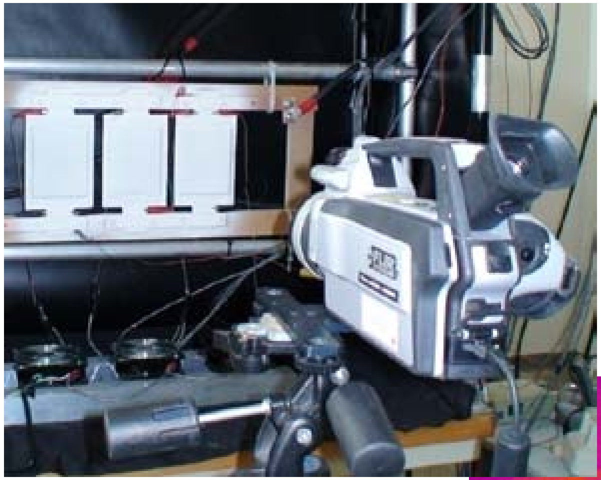


Nominal 2200 F
14 Wh/kg
3.8 V – 2.2 V

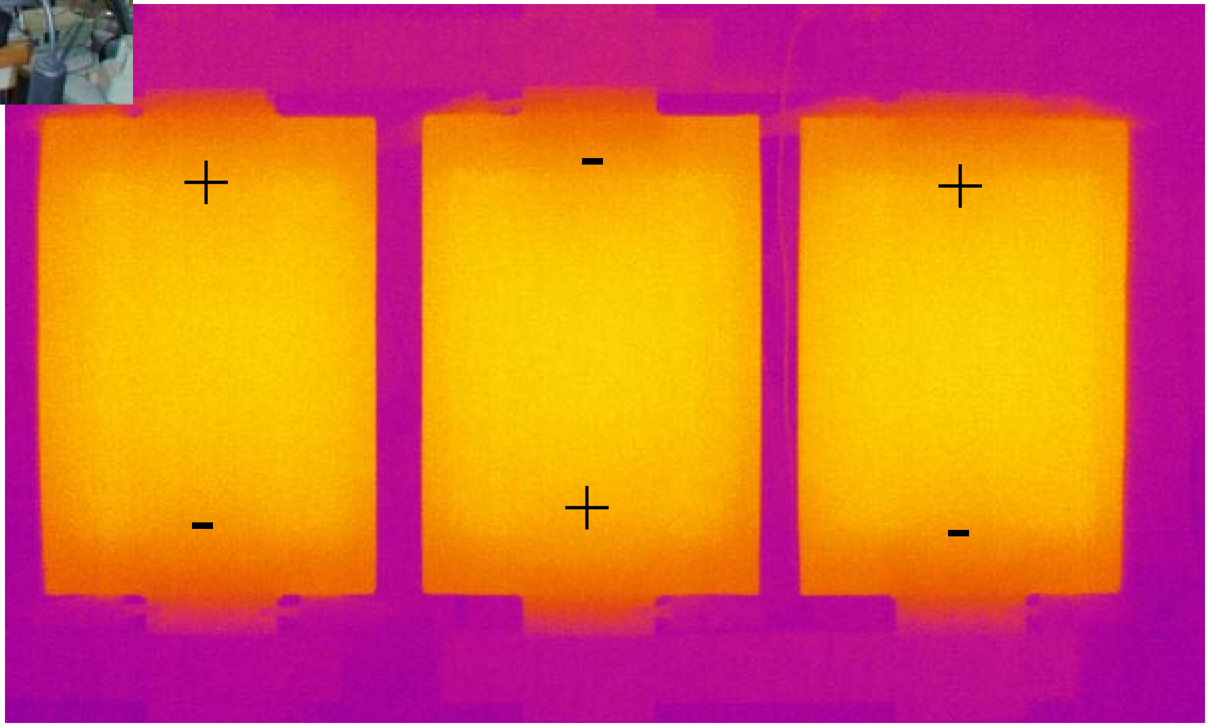
Measurement Items			2000F Series	Condition
Operating Temperature		Range	-20℃～70℃	
Rated Voltage		Maximum	3.8V	
		Minimum	2.2V	
Initial Property		Capacitance	2200F	10CA constant current discharge at 25℃
		ESR	1.4m Ω	ESR/1kHz
		Energy Density by Weight	14Wh/kg	10CA constant current discharge at 25℃
		Energy Density by Volume	25Wh/L	
Capacitance	-20℃	from 25℃	75%	10CA constant current discharge
	70℃	from 25℃	105%	
Heat Resistance		from Initial	90%	3.8V、70℃、and 1000hours
Cycle Test Performance		from Initial	90%	100CA constant current discharge 25℃、100K Cycles
Self Discharge		△ Voltage	Less than 5%	3 months at 25℃
Dimensions		Convex	138 X 106 X 8.5 mm	

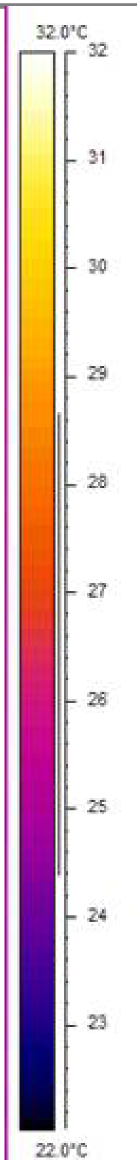
Source: www.jmenergy.co.jp/en/product.html

Infrared Thermal Imaging



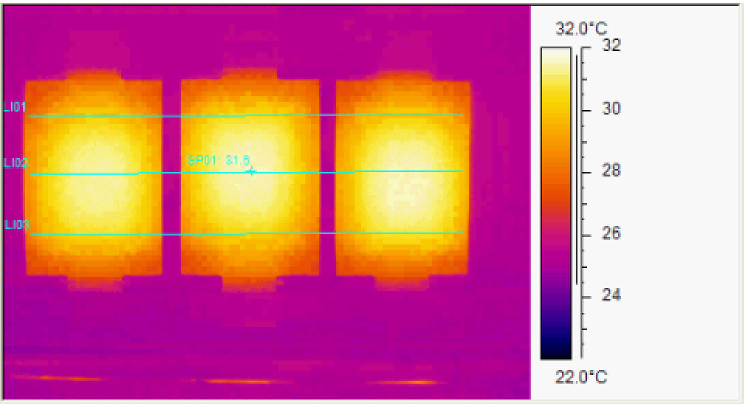
Temperatures: Ambient
Profiles: 50C, 100C, and Geometric Cycle





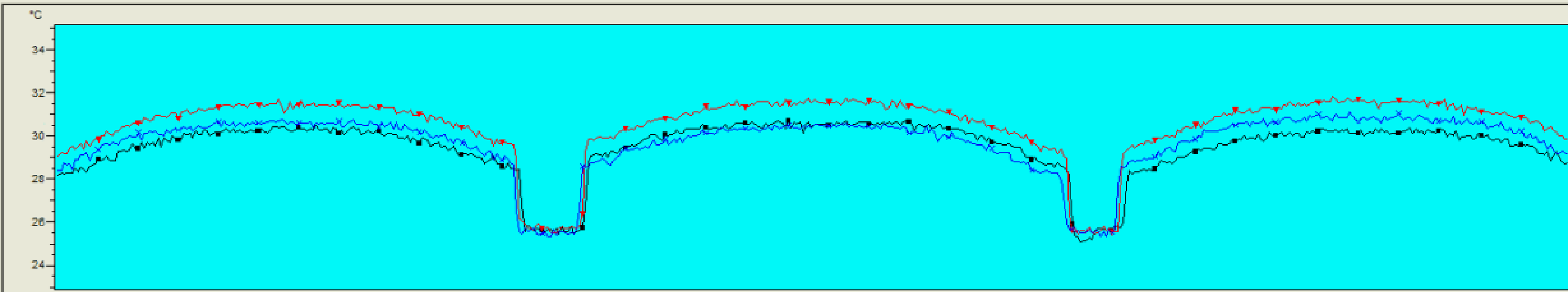
Cell #1 Cell #2 Cell #3

Thermal Image and Thermal Lines of 3 LIC Cells – 100 A Discharge



Analysis | Position | Obj. Par | Image | Text comment

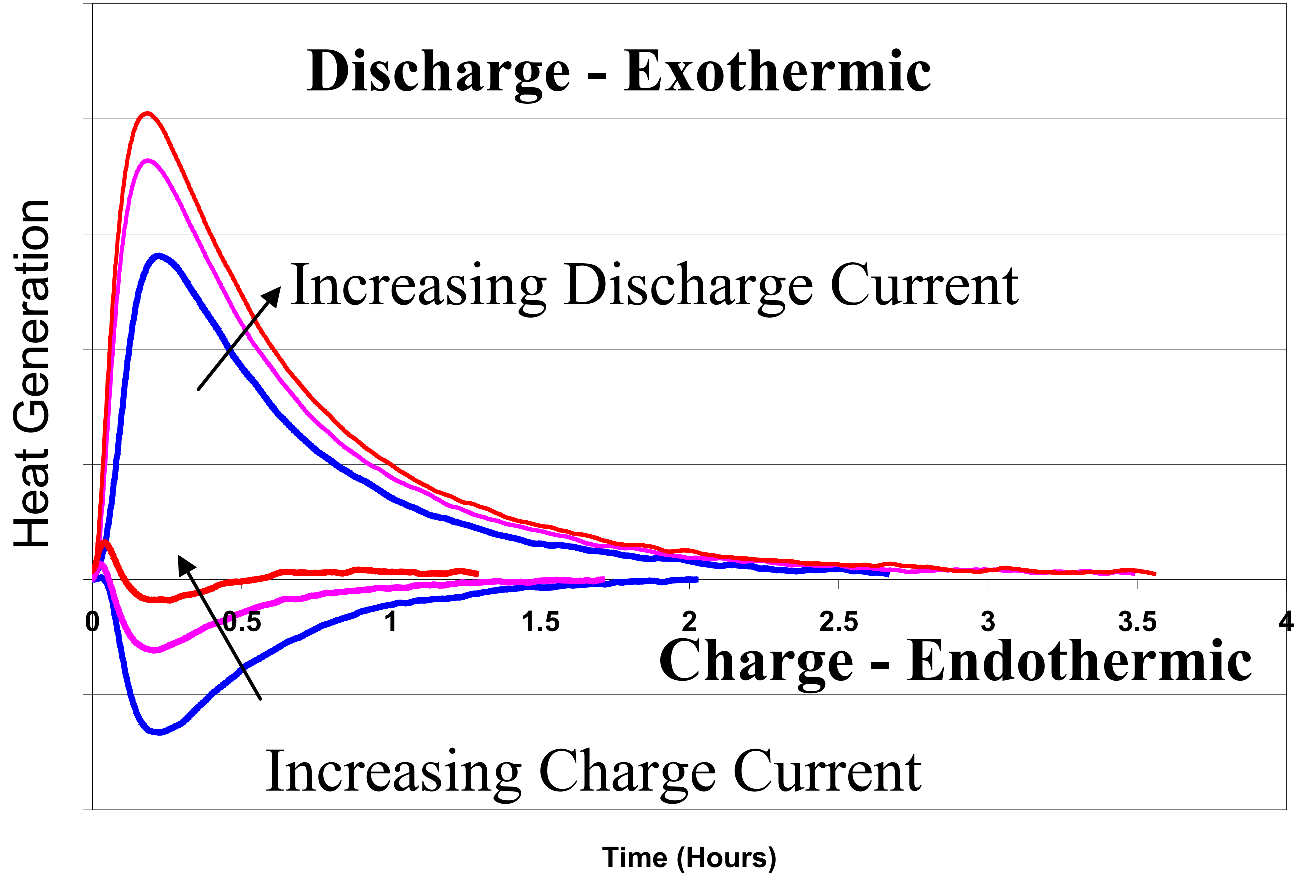
Label	Value [°C]	Min	Max	Max - Min	Avg	Stdev	Result	Expression
Image		24.0	31.9	7.9				
SP01	31.6							
LI01		25.1	30.7	5.7	29.5	1.3		
LI02		25.4	31.8	6.4	30.5	1.5		
LI03		25.4	31.1	5.8	29.7	1.4		



Label	Cursor	Min	Max	Avg	Cursor X	Cursor Y
LI01	-	25.1	30.7	29.5	-	-
LI02	-	25.4	31.8	30.5	-	-
LI03	-	25.4	31.1	29.7	-	-

Thermal Characterization in NREL Calorimeter Lithium Ion Capacitor 2200 F Cells

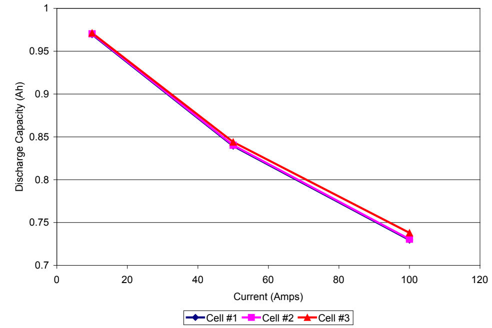
- Temperatures: +30˚C
- Profiles: CC discharge cycles

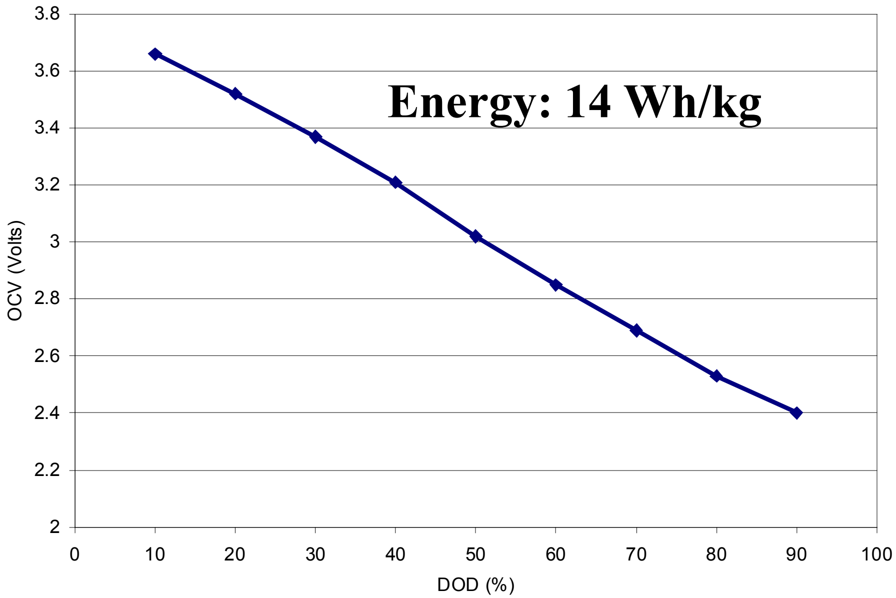


Calorimeter Response to Constant Current Charge/Discharge

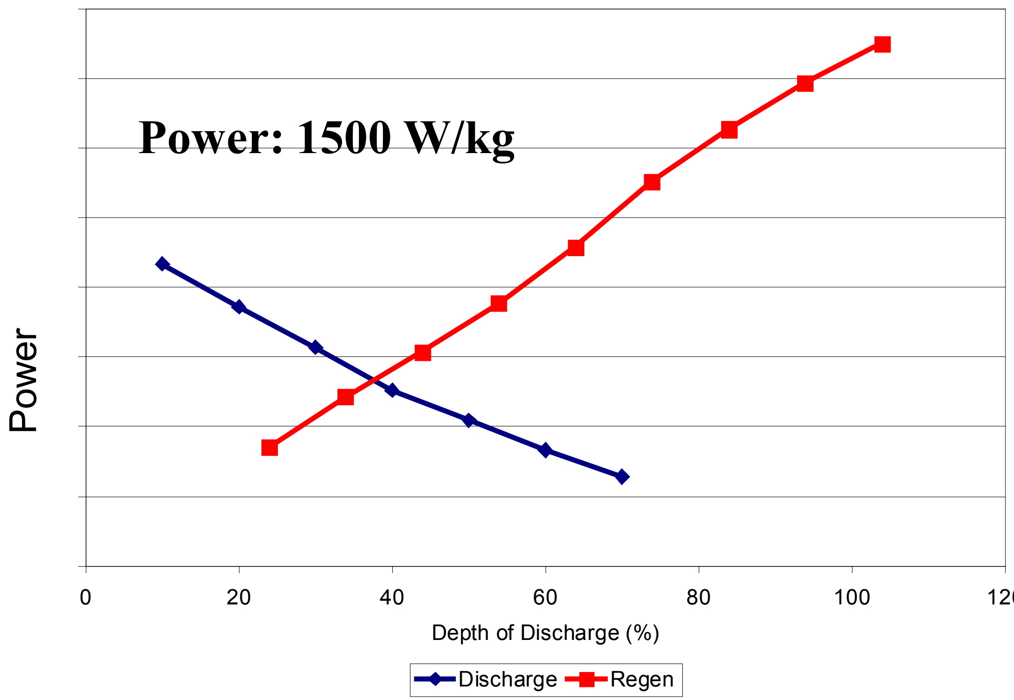
Electrical Characterization: Lithium Ion Capacitor Cells

- C/1, 10 C, 100 C, and HPPC Testing



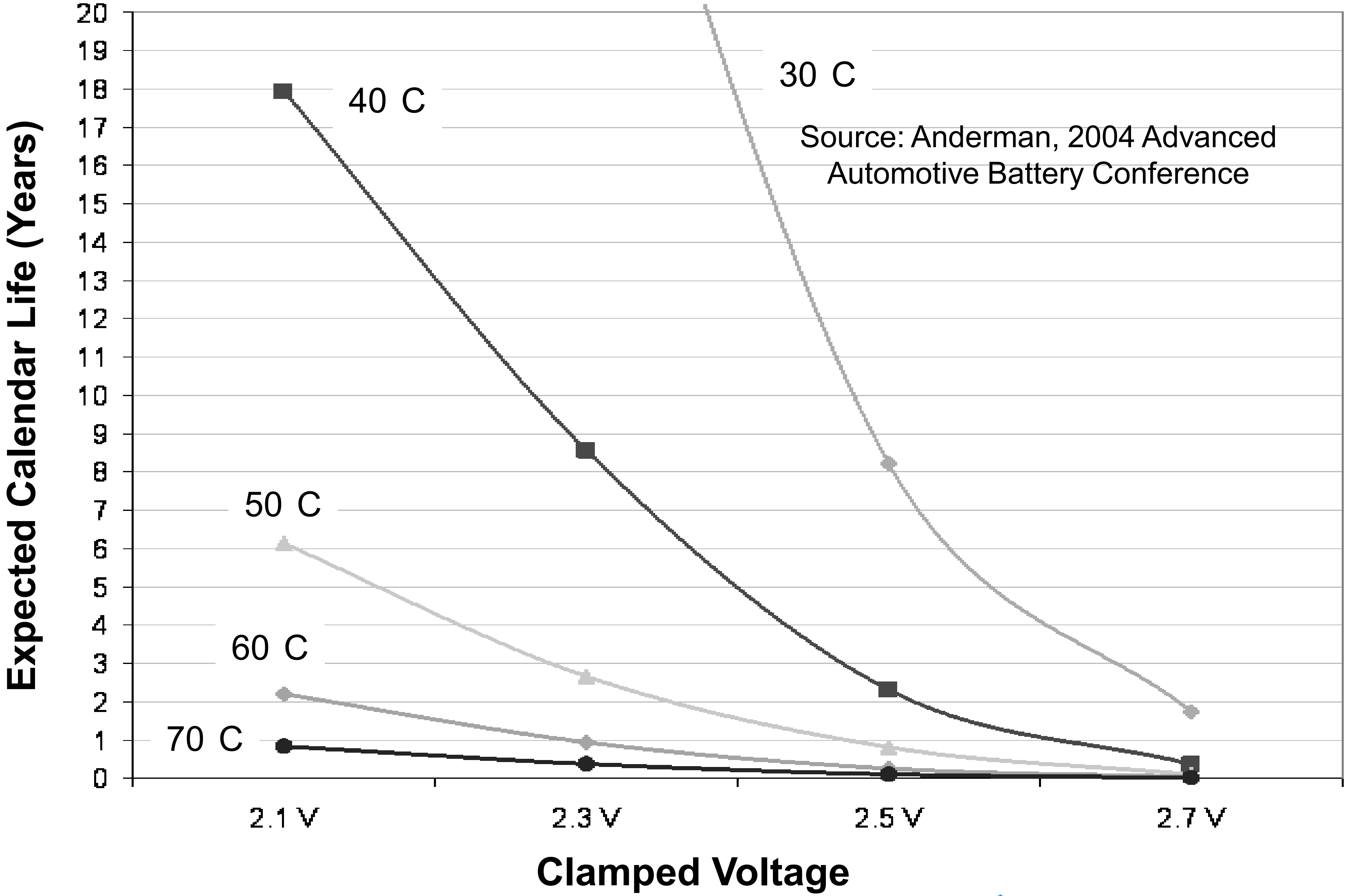


HPPC Discharge/Regen Power



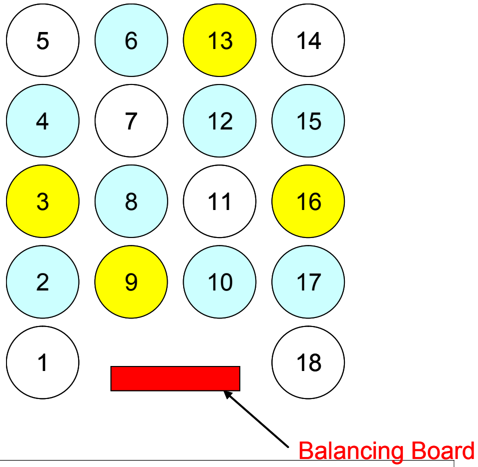
This asymmetric capacitor had high resistance; the next generation is claimed to be better.

Expected Calendar Life of Typical Current EDLC Technology Much Better Than Batteries if Stored at Low Voltages

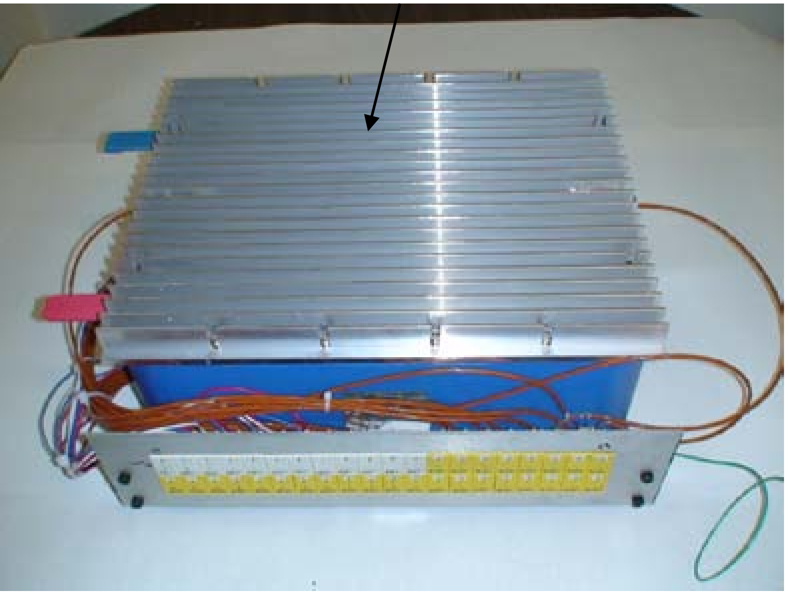


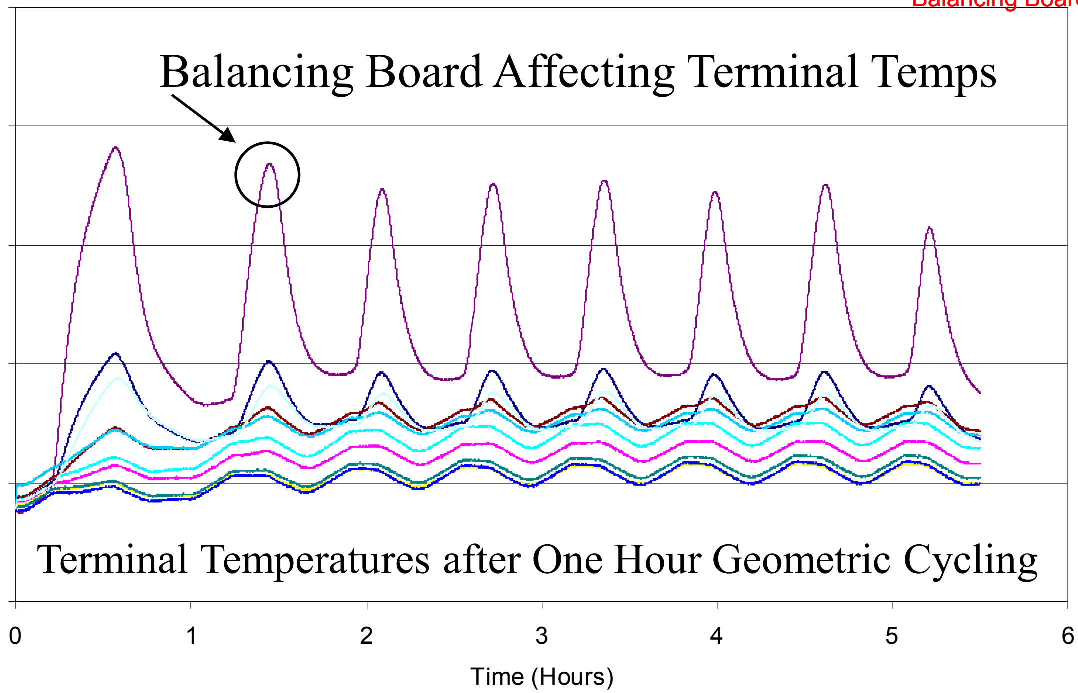
Thermal Evaluation: High-Voltage Ultracap Module

- Tested as part of USABC deliverable
- Eighteen (18) symmetric carbon-carbon ultracapacitors
- Tested under realistic conditions and operation
- Used different power profiles and chamber temperatures



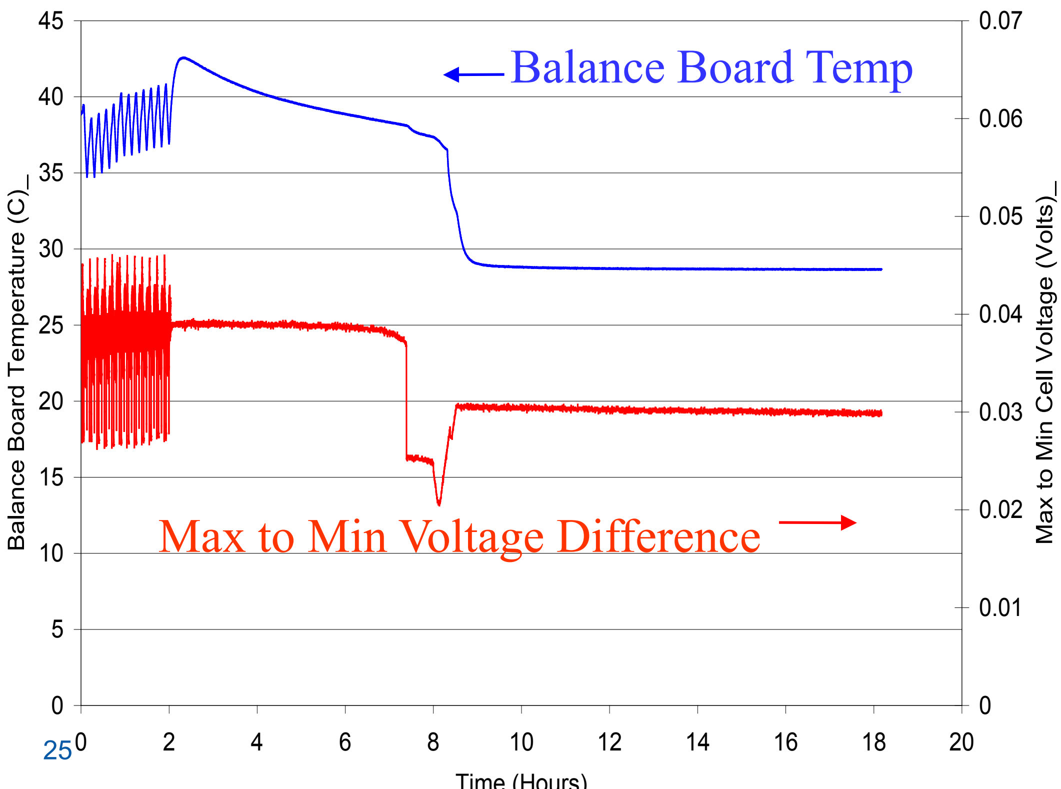
Heat from cells is conducted through the ends to the case and rejected through the top metal heat sink/fins.

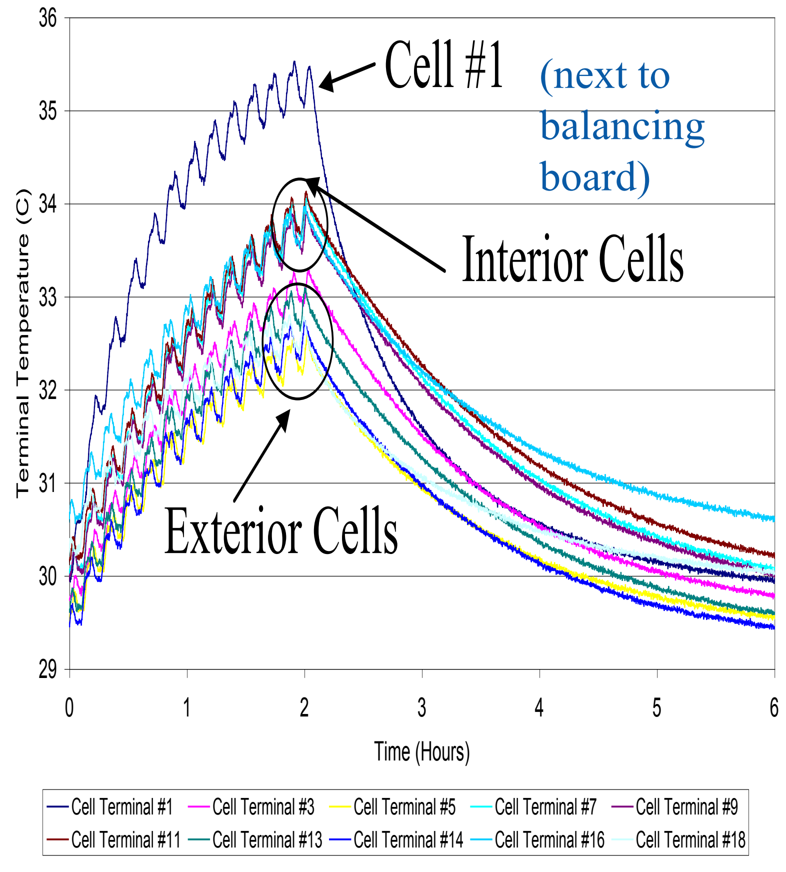




Thermal Evaluation: High-Voltage Ultracap Module

- Continuous US06 cycling for two hours
- Balancing board did a good job equalizing cells
- Energy drain for balancing could be a concern





Temperature difference less than 1.5°C except for Cell #1 which heated due to balancing board.

Concluding Remarks

- Ultracapacitors provide opportunity for modest fuel savings in hybrid cars
  - Idle-off: 5%-10% FE improvement and most likely to be implemented
  - Mild and full hybrid: 15%-25% FE improvement, possible
  - Plug-in hybrids: possible Ucap combined with batteries; cost??
- Competition from Li-ion is strong; ultracapacitors should provide “added value” to compete
  - Low-temp performance
  - Longer cycle and calendar life
- Asymmetric capacitors such as lithium ion capacitors have potential if power and cost are improved
- Thermal issues are important and must be taken into account to achieve the desired performance and life
- Lower cost is the key for increased market growth in automotive
- Micro and mild hybrids provide biggest opportunity for Ucaps in the short term; will be accelerated by new CAFÉ mandates

Acknowledgements

- Support provided by FreedomCAR and Fuel Partnership in the Vehicle Technologies Program of the U.S. Department of Energy
  — David Howell, Energy Storage Technology Manager

- Technical insight and support
  — Harshad Tataria, USABC/GM
  — Jim Banas, JSR Micro Inc.

nrel.gov/vehiclesandfuels/energystorage/publications.html