December 2 - 5, 2007

SUSTAINABILITY:
THE FUTURE OF TRANSPORTATION

ANAHEIM, CALIFORNIA USA

EVS 23

Thermal Management of Batteries in Advanced Vehicles Using *Phase-Change Materials*

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National Renewable Energy Laboratory, U.S.A.

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Electric Drive Transportation Association

In partnership with the World Electric Vehicle Association (WEVA)

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FreedomCAR & Fuel Partnership

NREL/PR-540-42544

Outline

*Using **P**hase-**C**hange **M**aterial for Automotive **B**attery **T**hermal **M**anagement*

- Background & Motivation
- Approach
- Analysis
  - Use in Intermittent Discharge Application
  - Use in HEV application
  - Use in PHEV application
- Summary

Background & Motivation

- Temperature is one of the most significant factors impacting both the performance and life of a battery
- More effective, simpler, and less expensive thermal management would assist in the further development of affordable battery packs and increase market penetration of HEVs and PHEVs
- Battery thermal management using phase-change material (PCM) has potential to bring benefits, such as passively buffering against life-reducing high battery operating temperatures
- *PCM technology should be assessed to determine whether it would improve upon existing vehicle battery thermal management technologies*

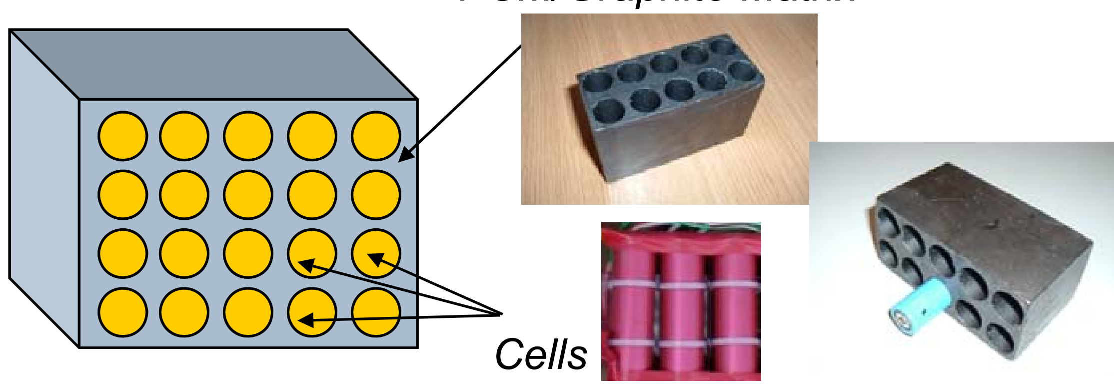
Prototype Technology

PCM-absorbed Carbon Matrix - AllCell®

Description: 18650 Li-Ion cells are surrounded by a high-conductivity graphite 'sponge' that is saturated by a phase-change material ('wax'). The matrix holds the PCM in direct contact with the cells, and the latent heat capacity to melt the PCM is intended to absorb the waste heat rejected by the cells during periods of intensive use.

Battery Module

PCM/Graphite Matrix



NOTE: This module is not a optimized design for readily use in HEV/PHEV

Perceived ***Advantages*** & ***Disadvantages*** of *Using PCM for Vehicle Battery Thermal Management*

- Possible Advantages
  - Reduced peak temperatures
  - Better temperature uniformity
  - Reduced system volume
- Possible Disadvantages
  - Heat accumulation
  - Additional weight
  - Undesirable thermal inertia

Approach

Acquired Product/Material Samples from AllCell®

TEST: Property/Performance Measurement & Validation

MODEL: Module/System Level Analysis

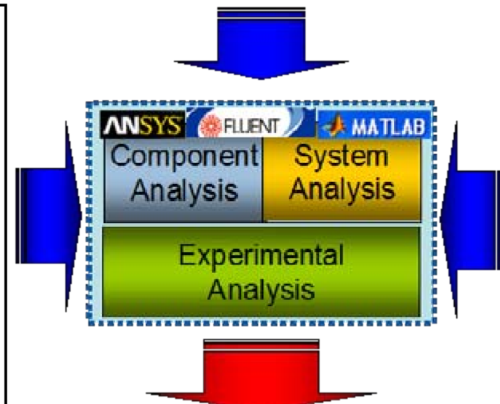
Evaluation for use in HEV/PHEV

Cell Characteristics

Q?
Calorimeter Test
R_{int} / Efficiency

PCM Module Design

- Matrix Dimensions
- PCM Amount
- Melting Temperature
- Cell Array Config.
- Additional Cooling



THERMAL RESPONSES Of SYSTEM

Battery Temperature History
Frequency/Duration of Exposure to High Temperatures

Operation Scenario

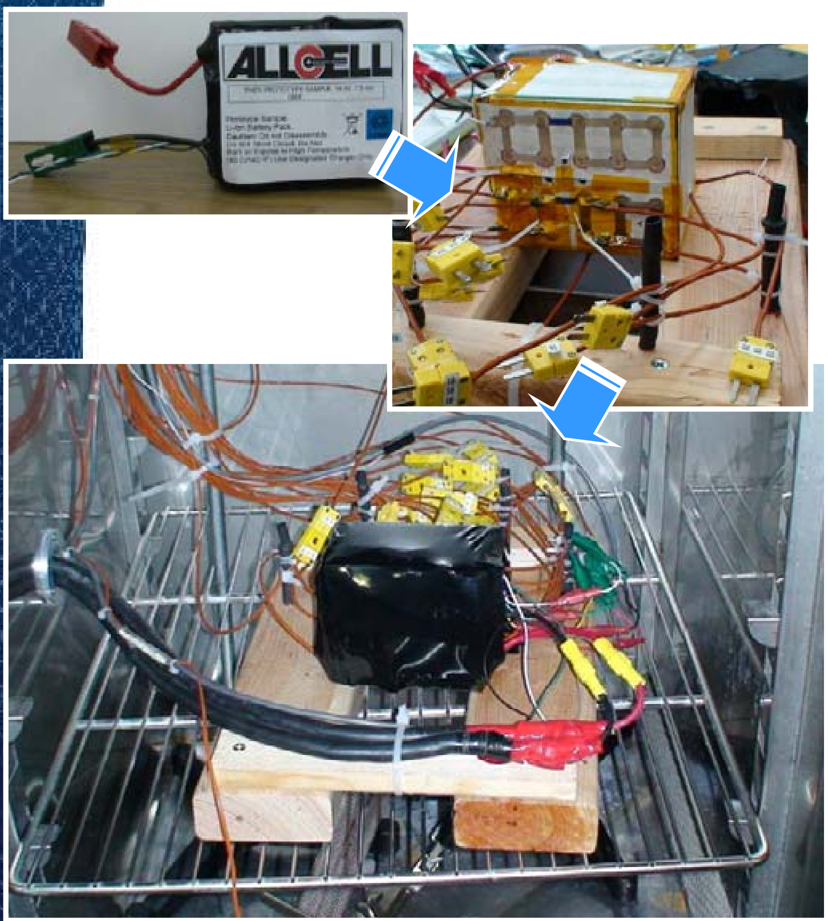
Standard Driving Profile
Real World Survey

Vehicle Selection
Control Strategy
Component Sizing
Grade

Vehicle Simulation
Vehicle Drive Data

Battery Power Profile in Vehicles (HEV,PHEV)

Prototype Module Test



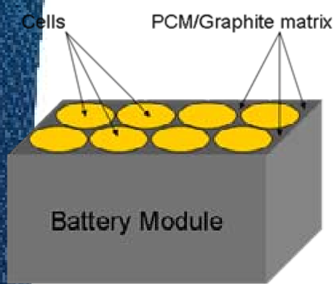
- Evaluate thermal management performance of PCM matrix in the prototype module
- Provide data for model validation and improvement

- Instrument for voltage(4), current(1) and temperature(21) distribution;
  - K-type calibrated thermocouples
  - ±0.35°C uncertainty
- Connect to battery cycler and place in environmental chamber

Model Description

Thermally Lumped System Model

system level analysis: temporal variation of battery system thermal responses



- Assume fast internal heat transfer
- Reasonable for the prototype module, where the system Biot number is roughly 0.005 (<<0.1).

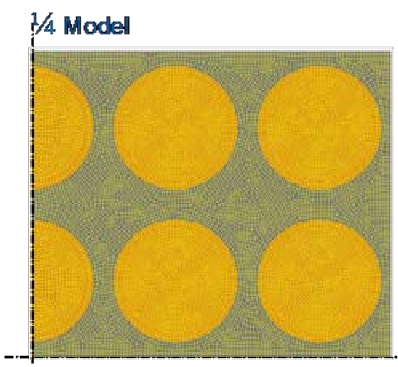
$$M_{sys}\left(Cp_{sys} + D\lambda_{sys}\right)\frac{dT}{dt} = hA_{surf}\left(T_{amb} - T\right) + Q_{gen}$$

$$D = \frac{e^{-(T - T_{melt})^2 / \delta T^2}}{\sqrt{\pi \delta T^2}}$$

Multi-dimensional Model

Multi-dimensional analysis: spatial temperature imbalance in a module

- Developed with finite volume method (FVM)
- Address thermal distributions through a module
- Ignore fluid motion of melted PCM in a porous carbon



$$\rho \bar{c}_p \frac{dT}{dt} = \nabla\left(k\nabla T\right) + q'''$$

$$\bar{c}_p = \left(c_p + D\lambda\right)$$

Analysis & Evaluation

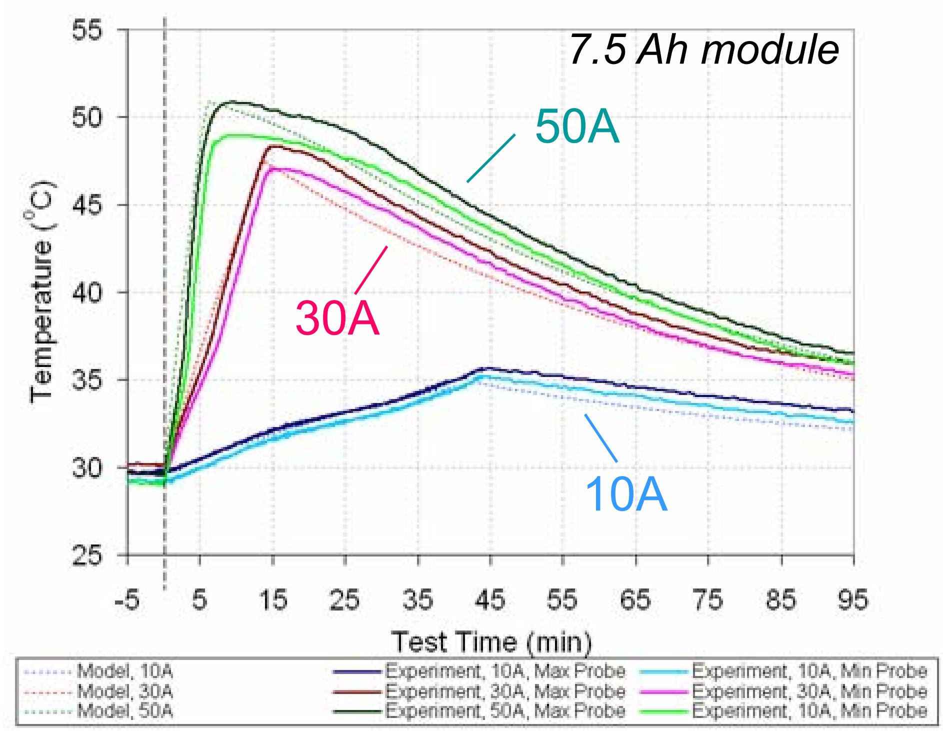
1. *Analysis of Intermittent Discharge Application*
2. *Analysis of Aggressive HEV Application*
3. *Analysis of PHEV10 Cycling Application*

Analysis & Evaluation

1. **Analysis of Intermittent Discharge Application**
2. *Analysis of Aggressive HEV Application*
3. *Analysis of PHEV10 Cycling Application*

Single Discharge

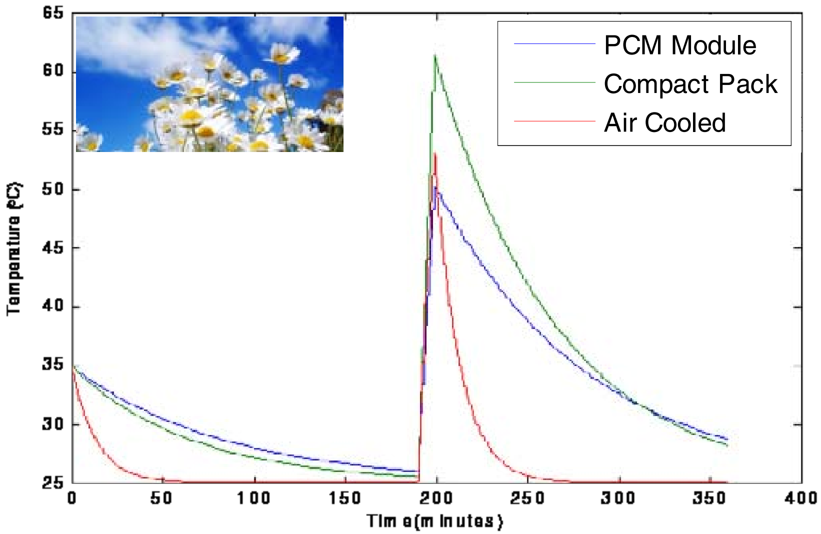
- Limited duration of heat release
- Finite heat generation
  - Possible to quantify maximum heat for PCM
- Usually long rest period between uses
  - No need for fast heat removal from the system



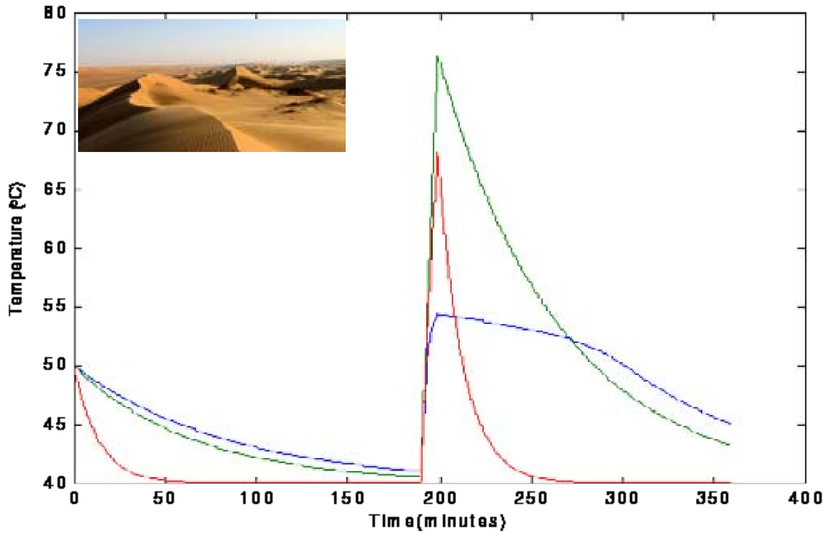
- Model shows good agreements with experiments in general
- Module temperature stays below the PCM melting temperature (55°C) under 30°C ambient temperature discharge event

Thermal Performance Comparison
under Different Ambient Conditions
– 40A single discharge for 9 minutes

at 25°C ambient → no phase change



at 40°C ambient → phase change

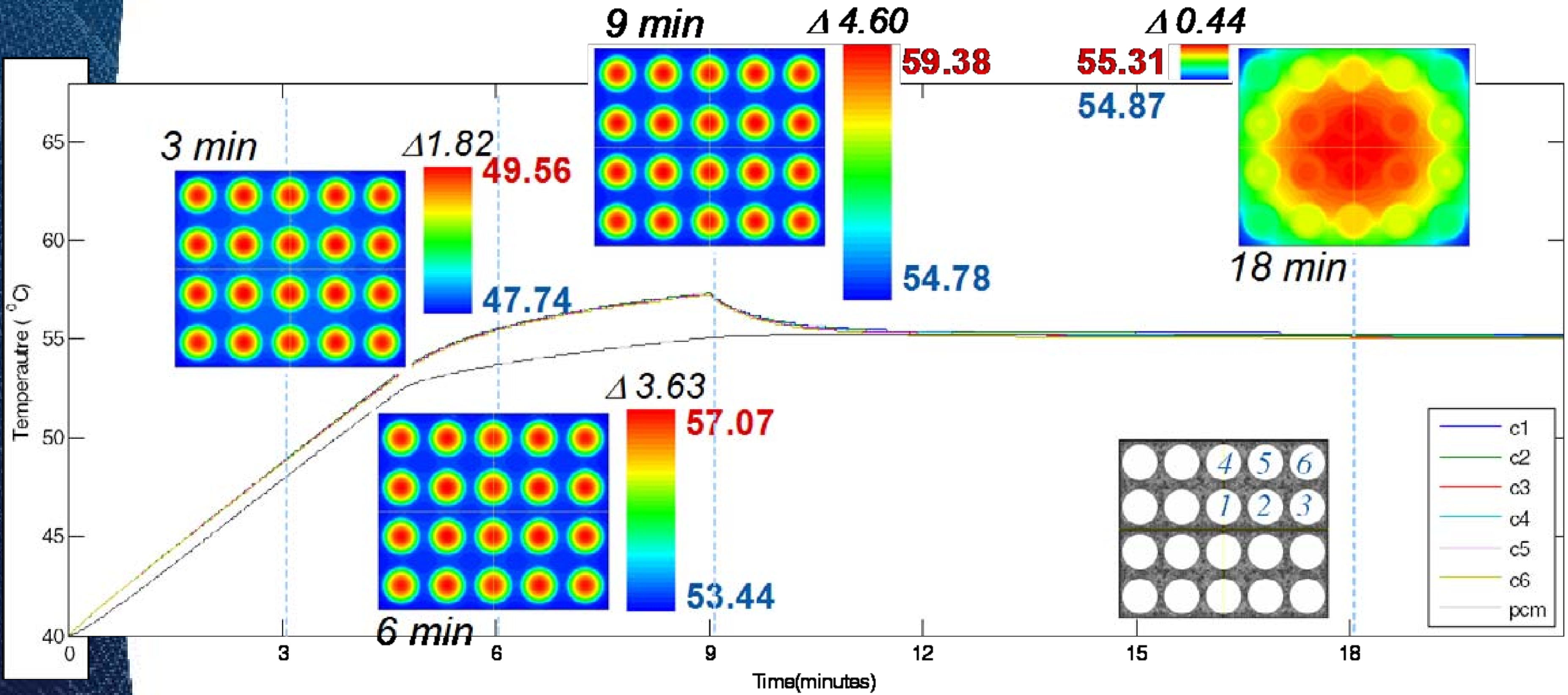


- Peak temperatures at PCM module and Air-cooled module were comparable under room temperature discharge case
- PCM latent heat limits the peak temperature of module under high temperature environment use

Temporal & Spatial Temperature Variations

40A Single Discharge at 40°C Ambient

- PCM Phase Change Limits the Cell Temperature Increase



Average Temperatures of Cells and Matrix

Concluding Remarks on
Use in Intermittent Discharge Application

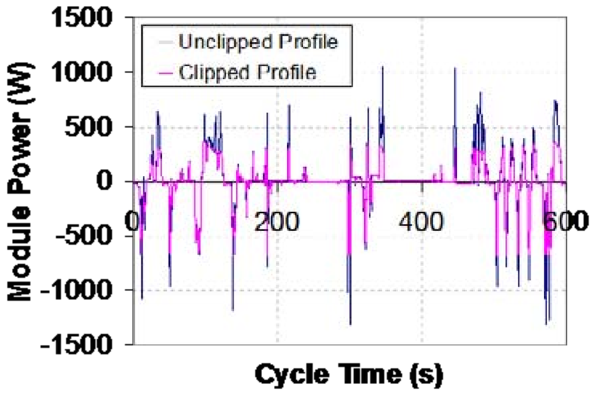
- PCM effectively prevents the exposure to battery damaging high temperatures especially for high rate discharge under high temperature ambient condition
- Fast heat transfer through highly conductive carbon matrix keeps the temperatures of cells in a module fairly uniform
- Passive thermal management using the PCM technology would show excellent performance in intermittent discharge applications

Analysis & Evaluation

1. Analysis of Intermittent Discharge Application
2. **Analysis of Aggressive HEV Application**
3. Analysis of PHEV10 Cycling Application

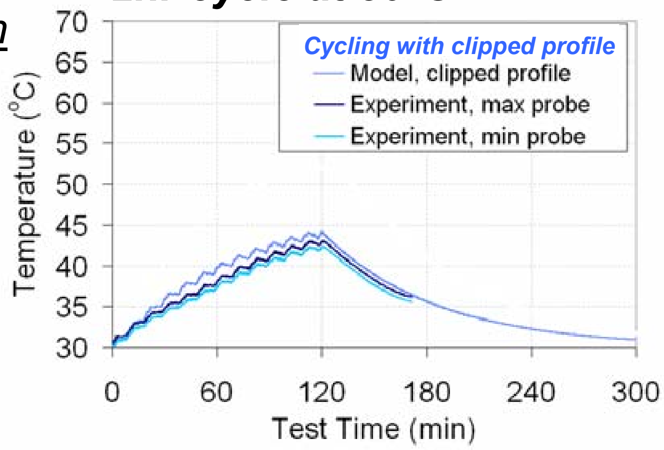
Prototype Module Test Profile for Mid-size Sedan HEV: US06

- Prototype P/E ~ 10 kW/kWh
  - Underpowered pack for HEV
  - Oversized in energy content
- Developed electrical test profile using vehicle simulations
- Profile was clipped with continuous charge/discharge limits

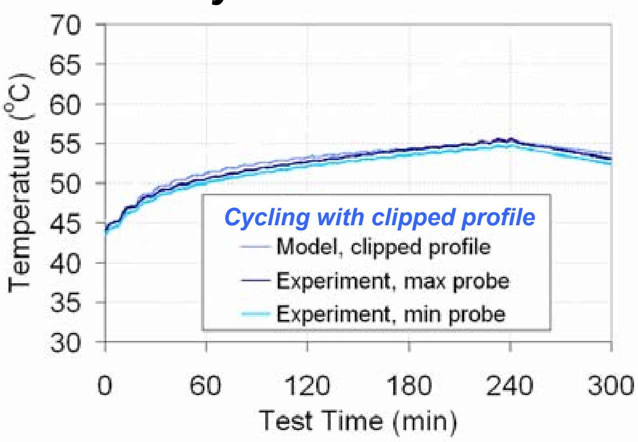


Model Validation for HEV Cycle

2hr cycle at 30°C



4hr cycle at 45°C

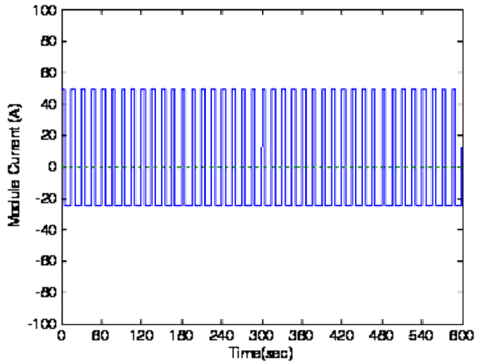


Continuous Cycling

Model Investigation: Periodic Steady State

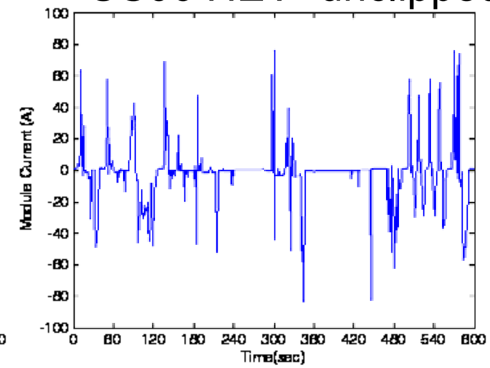
- Continuous cycling
  → Continuous heat
- Heat rejection rate
  → Equilibrium system T

Geometric Profile



→ *Q=45 W/module*

US06 HEV -unclipped



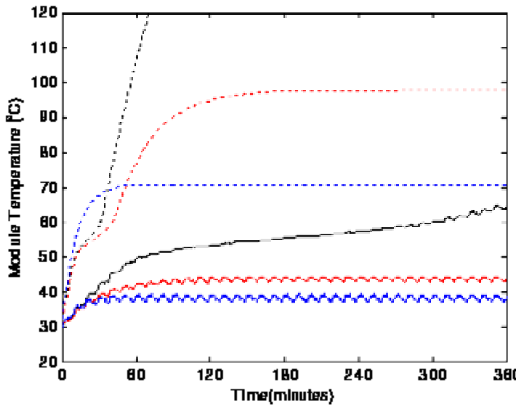
→ *Q=9.2 W/module*

- - - - - Geometric
——— US06

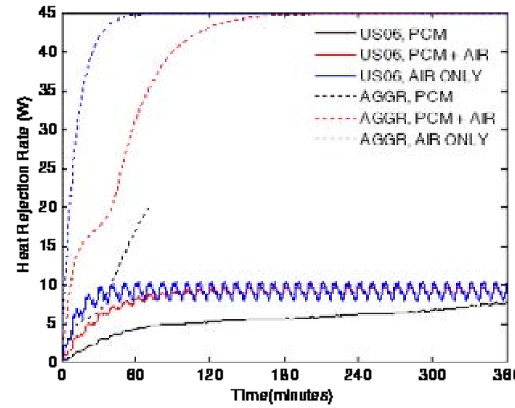
PCM only
PCM + Air
Air only

Initial T=30, Air T=30

Module Temperature



Heat Rejection Rate

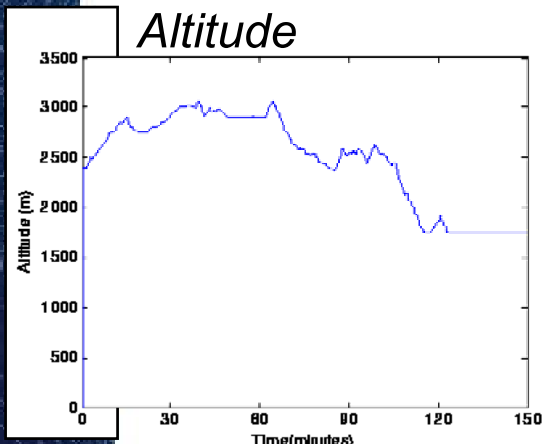


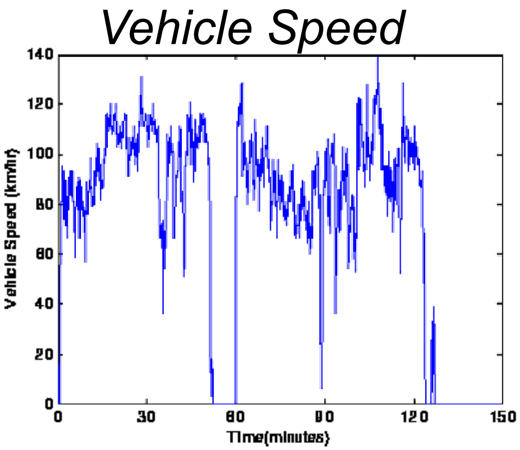
45

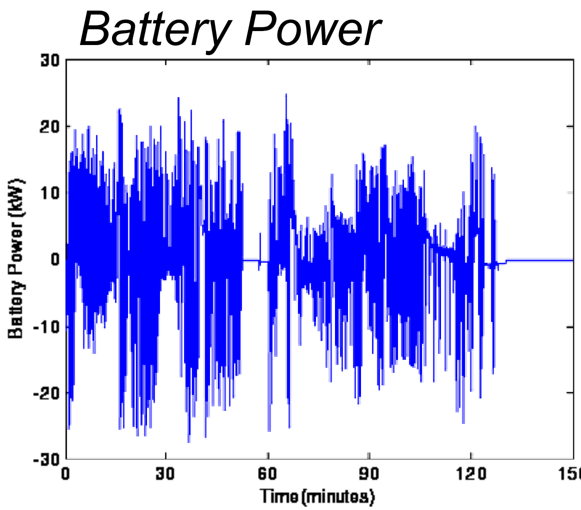
9.2

Real World 'HEV' Drive

- 2 hour mountain drive
  - Start from mountain
  - To the suburb of Denver
- "Prius" drive with stock NiMH pack
  - Collected data during the drive





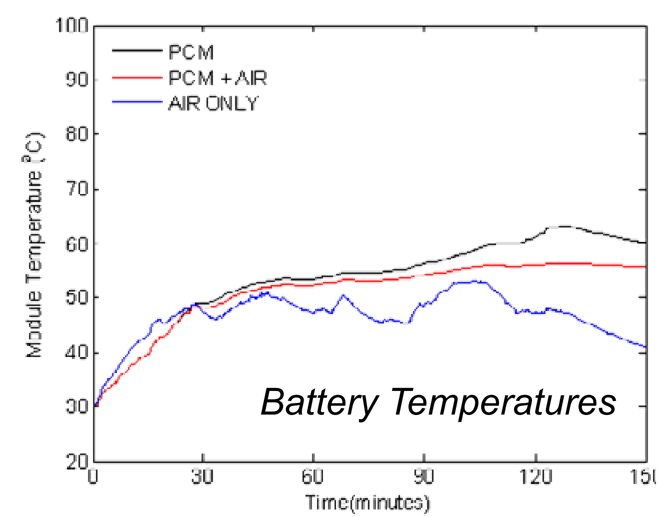


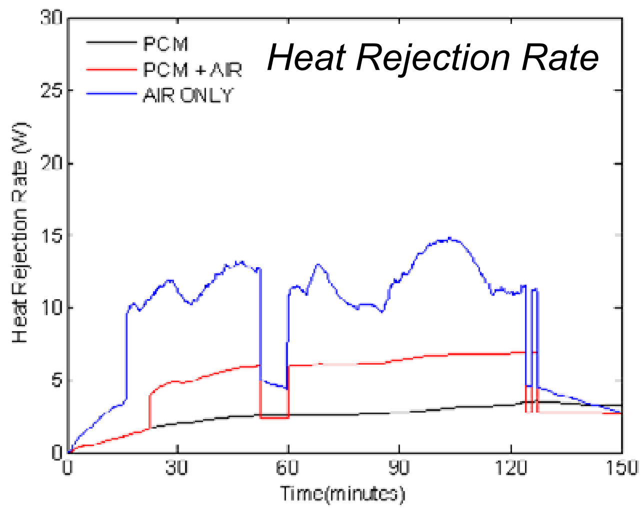
Thermal Performance with a *Virtual Li-Ion Pack* in Real World 'HEV' Drive

Virtual Module

- Identical electrical response
- 12 26650 cells (6p 2s)
- 3mm spacing with 4x3
- 94 % efficiency
- Replace 1 stock module

	Prius Stock NiMH Module	Virtual Li-Ion Module
P/E	28	27
Specific Power (W/kg)	1300	1820
Specific Energy (Wh/kg)	46	67
Mass Density (kg/m³)	~2500	~2000
Specific Heat (J/kg.K)	~850	~850

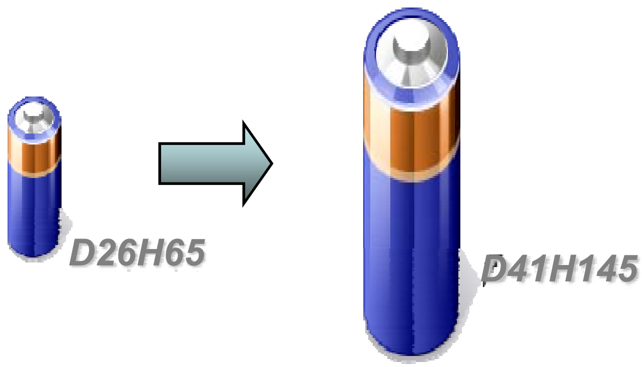


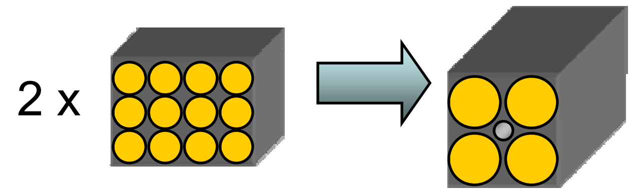


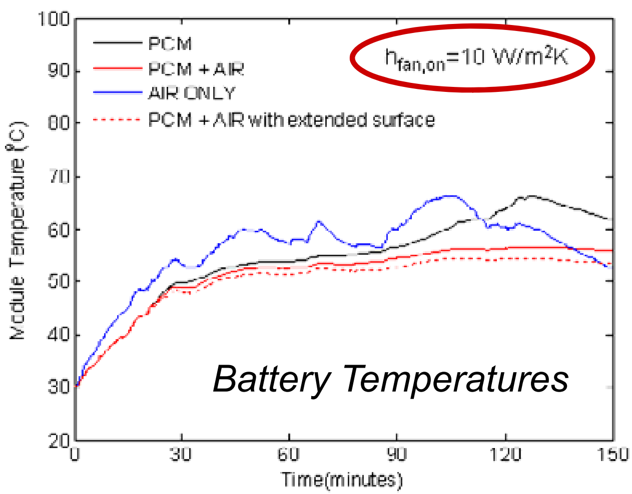
- $h = 10\ W/m^2K$
- $\overline{Q} = 9.9$ W/module

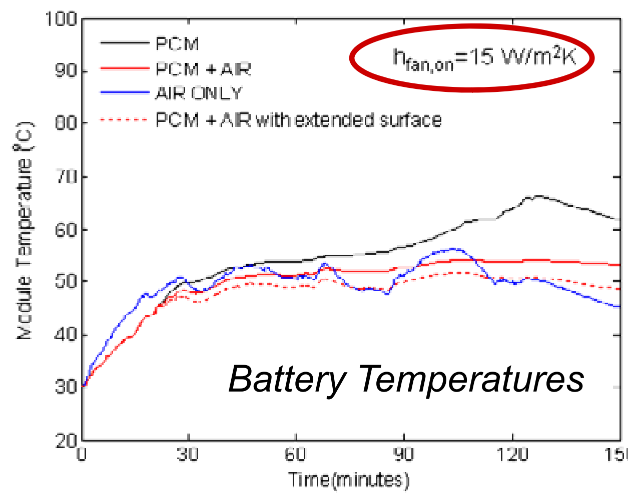
PCM only
PCM + Air
Air only

Thermal Responses with a *Large Cell Pack* *in Real World 'HEV' Drive*



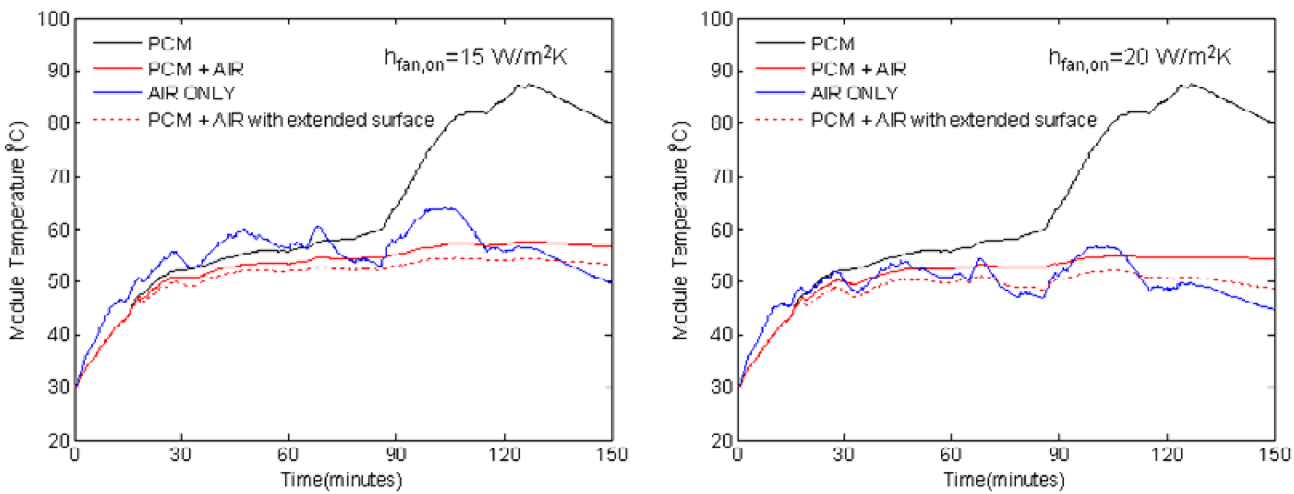




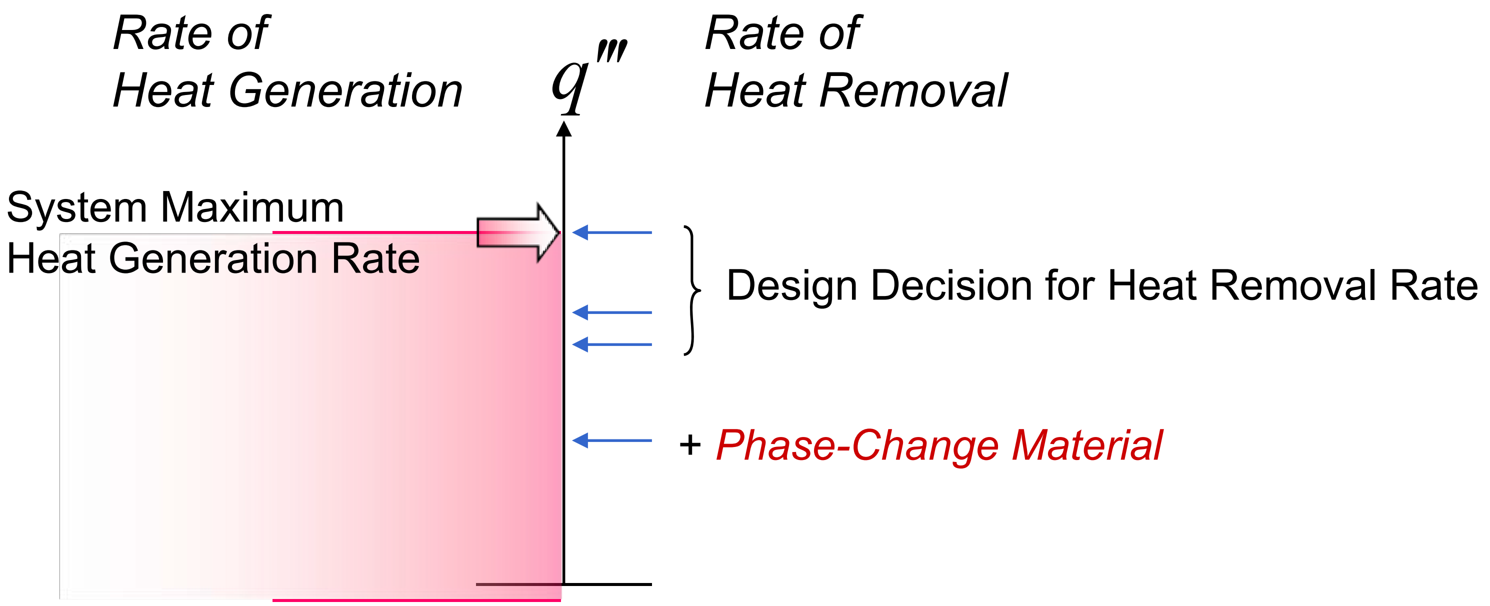


Thermal Responses with a *Large Power Cell Pack in Real World 'HEV' Drive*

- A more advanced battery would have fewer cells to meet the vehicle power requirements
  - Higher power cells could cause higher volumetric heat
- Brief Investigation
  - Doubling Power Rate
  - Efficiency Increase, 94% → 96%



Concluding Remarks on
Use in HEV application



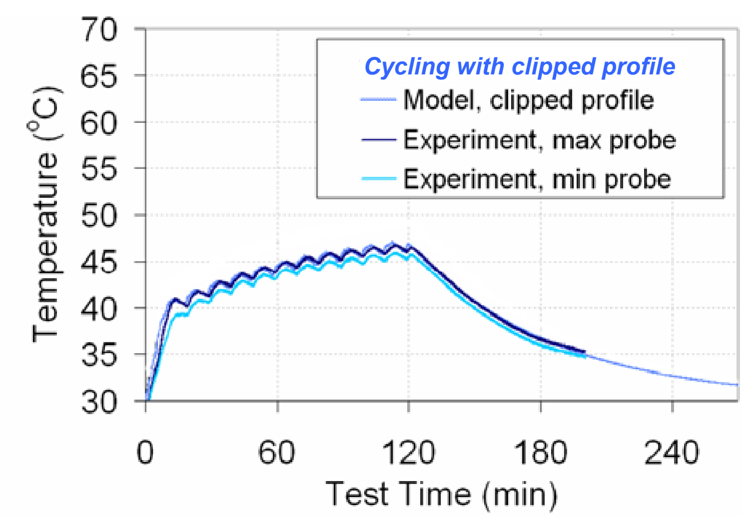
Analysis & Evaluation

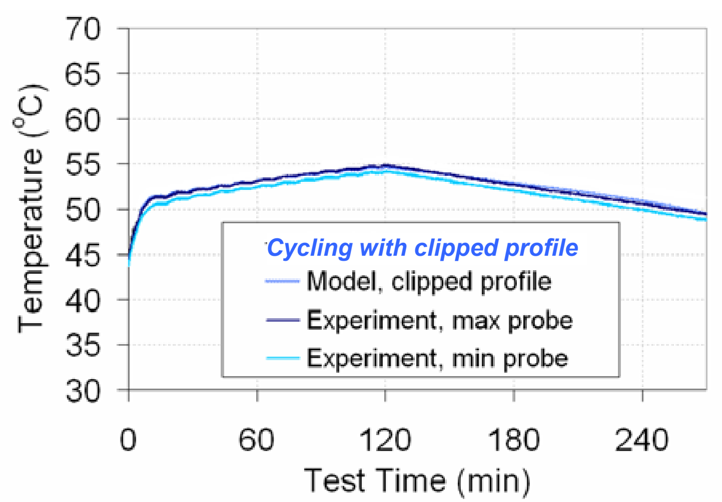
1. *Analysis of Intermittent Discharge Application*
2. *Analysis of Aggressive HEV Application*
3. ***Analysis of PHEV10 Cycling Application***

Prototype Module Test for Mid-size PHEV10 - US06 Cycle

- Typical PHEV drive =

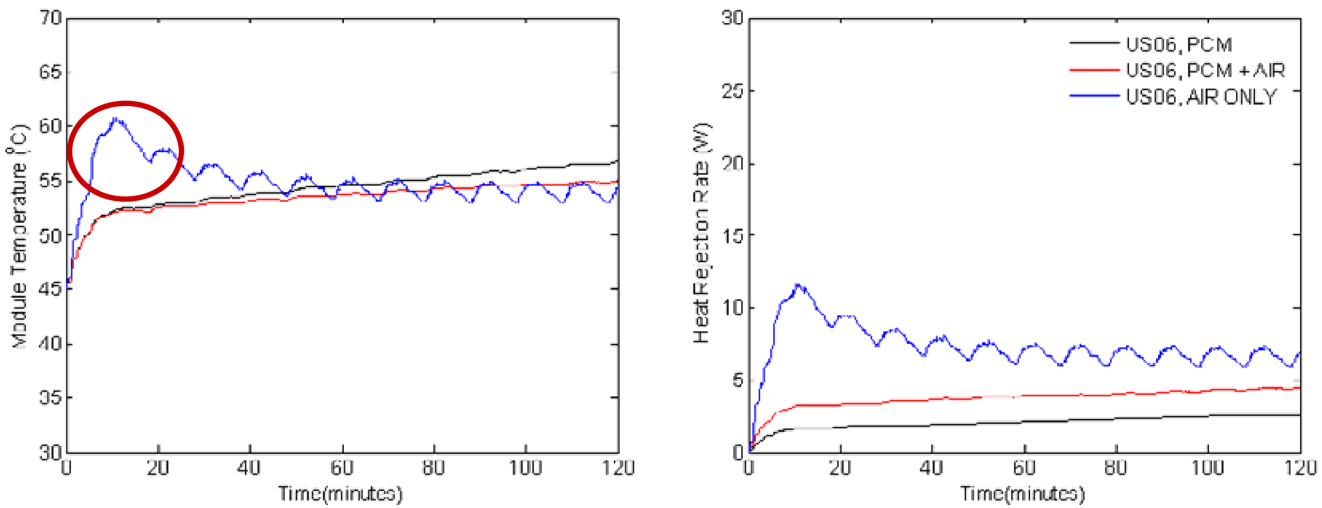
  - Initial EV drive (Charge Depleting) + Flowing HEV drive (Charge Sustaining)
  - Thermally Aggressive Operation + Thermally Moderate Operation





PHEV10 Battery Temperature Response at high ambient temperature (45°C)

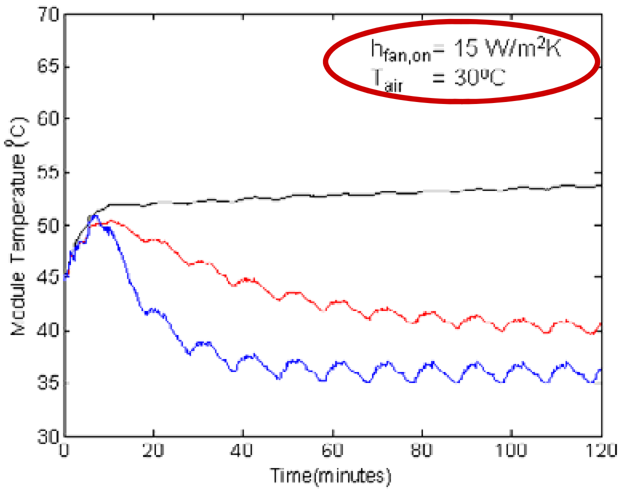
h=10 W/m²K

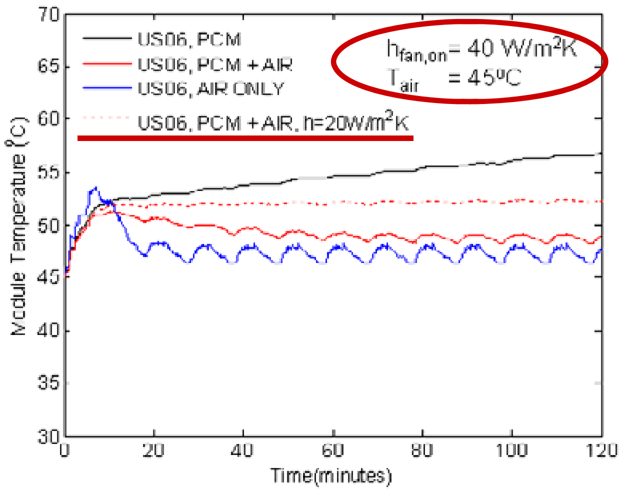


- Initial thermally aggressive Charge Depleting drive causes temperature excursion to over 60°C in air-cooling battery

Methods for Limiting Temperature Excursion during EV Drive

- If available,
  - Use the thermally regulated cabin air (30°C) for battery cooling
- If not,
  - Incorporate a high heat transfer coefficient (40W/m²K) design
  - Limit EV drive at high battery temperatures
  - Combine PCM with moderate heat transfer coefficient (20W/m²K) design





Concluding Remarks on

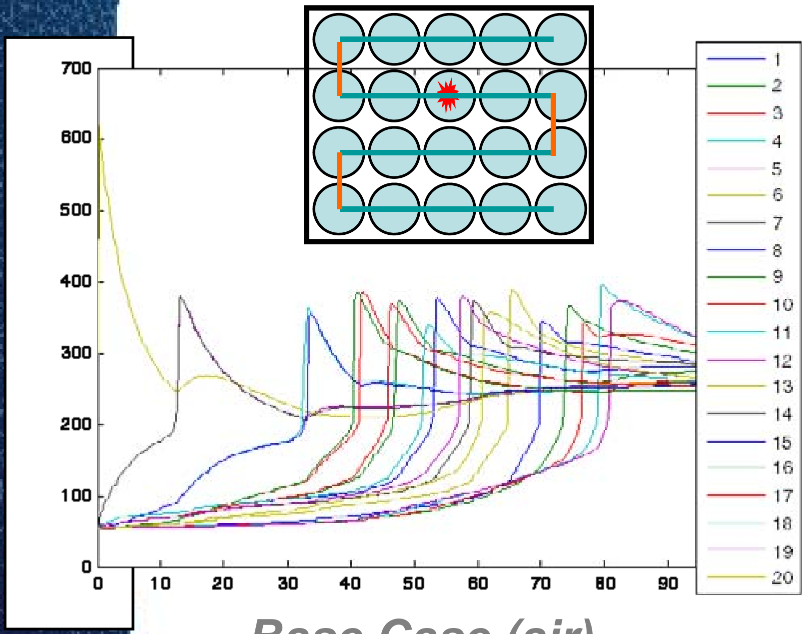
Use in PHEV application

- In short EV range PHEVs, combining PCM for addressing aggressive initial EV drive can minimize the size of air cooling systems.
- In large EV range PHEVs, the batteries may have enough thermal mass by themselves to provide a buffer against intermittent temperature spikes.

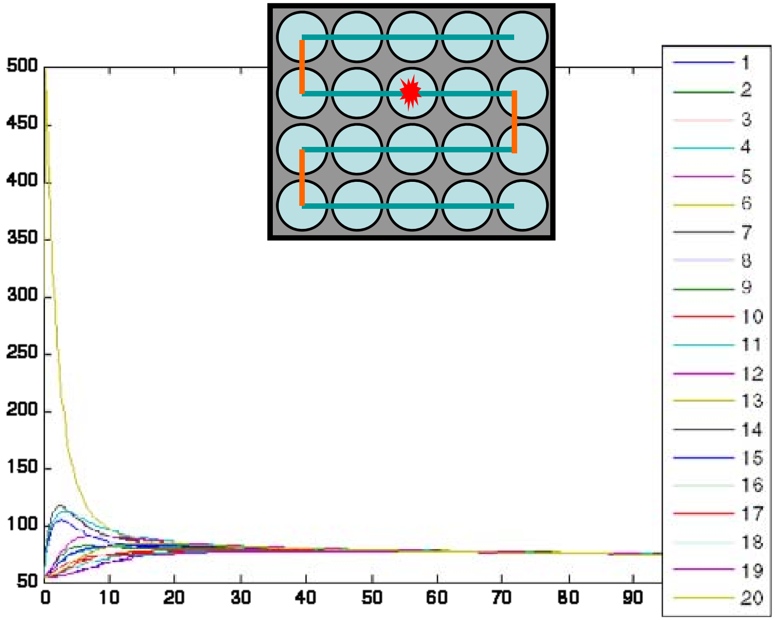
Impact of "PCM/Graphite Matrix" on Thermal Runaway Propagation in a Module

(Results from G.-H. Kim et al. , 212th ECS, Washington, DC, Oct, 2007)

If one cell goes into thermal runaway, will it propagate to other cells and how?



Base Case (air)

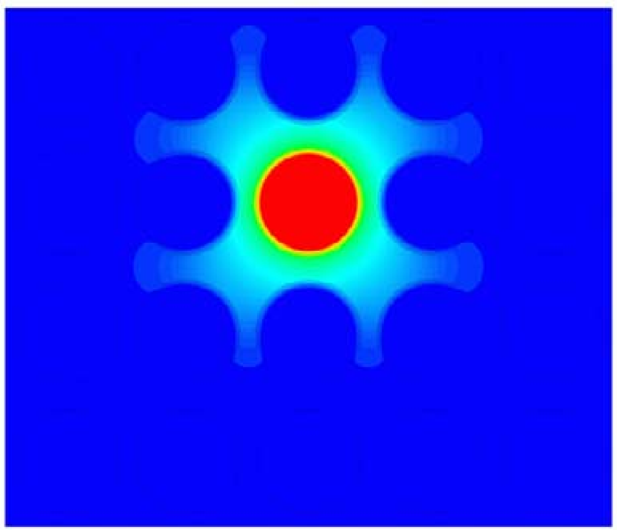


PCM/Graphite Matrix Imbedded

Rather than air, highly conductive PCM/Graphite Matrix filled the space between the cells in the module.

Multi-Dimensional Analysis
Thermal Abuse Reaction Model

Temperature



Reaction Heat from SEI decomposition

Summary

- Battery thermal management using PCM shows excellent performance in limiting peak temperatures at short period extensive battery use
- Using PCM without convective cooling methods may not applicable in HEV/PHEV applications
- Combining PCM method would allow smaller air cooling system and less need to limit battery power output in high-temperature conditions
- Vehicle designers will need to weigh the potential increase in mass and cost associated with adding PCM against the anticipated benefits

Acknowledgments

- DOE FCVT Energy Storage Program Support
  - Tien Duong
  - Dave Howell
- Technical Support and Supplying Batteries and Information
  - Said Al-Halaj (IIT/AllCell)
  - Riza Kizilel (IIT)
  - Peter Sveum (AllCell)

EVS 23

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