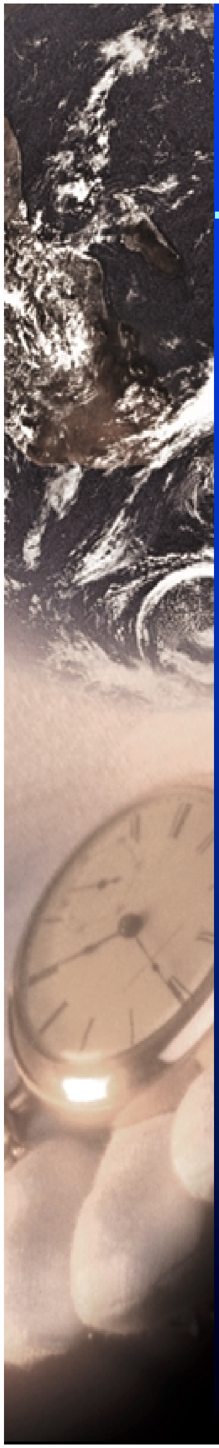
Battery Thermal Management in EVs and HEVs: Issues and Solutions

Ahmad A. Pesaran, Ph.D.
National Renewable Energy Laboratory
Golden, Colorado

www.ctts.nrel.gov/BTM

First Annual
Advanced Automotive Battery Conference
Las Vegas, NV
February 5-8, 2001

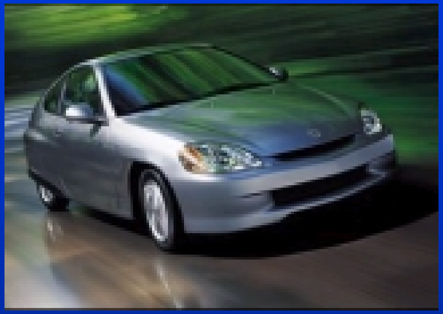


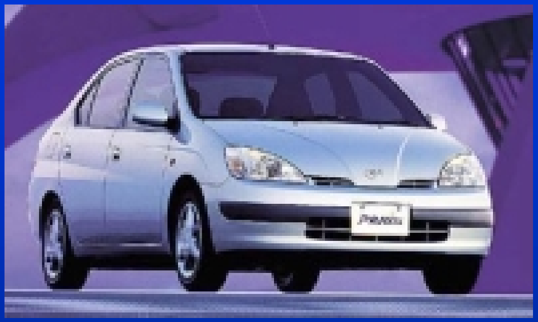
Presentation Outline

- Background
- Attributes of a thermal management system
- Thermal characteristics/behavior of batteries
- Discussion
  - active vs. passive
  - cooling vs. cooling/heating
  - series vs. parallel flow
  - liquid vs. air
  - VRLA, NiMH, Li-Ion
- Concluding Remarks

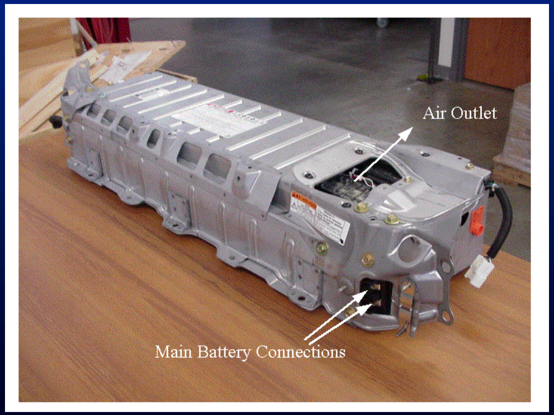
Background

- Electric and hybrid electric vehicles in the market

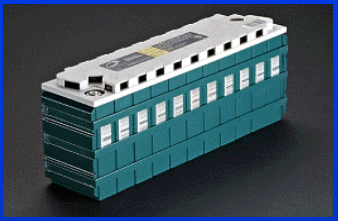




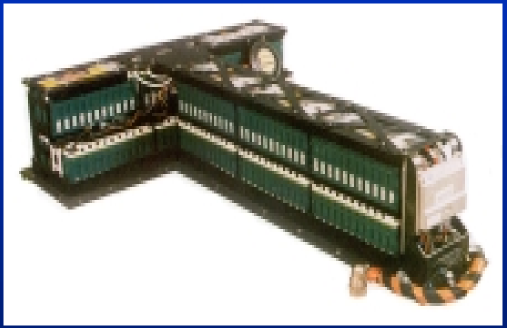
- EV and HEV success depends on battery performance, life, and cost



Battery Temperature is Important



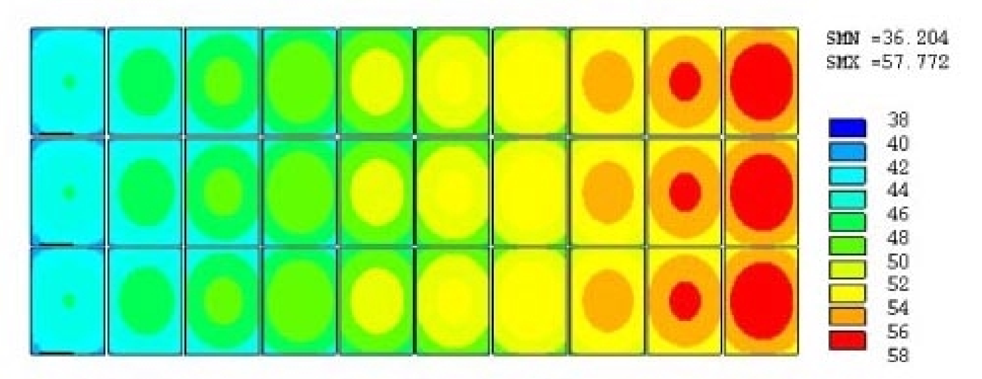
- Temperature affects battery:
  - Operation of the electrochemical system
  - Round trip efficiency and charge acceptance
  - Power and energy
  - Safety and reliability
  - Life and life cycle cost



Battery temperature affects vehicle performance, reliability, safety, and life cycle cost

Battery Pack Thermal Management Is Needed

- Regulate pack to operate in the desired temperature range for optimum performance/life



- Reduce uneven temperature distribution in a pack to avoid unbalanced modules/pack and thus, avoid reduced performance
- Eliminate potential hazards related to uncontrolled temperature

Trend in Battery Thermal Management

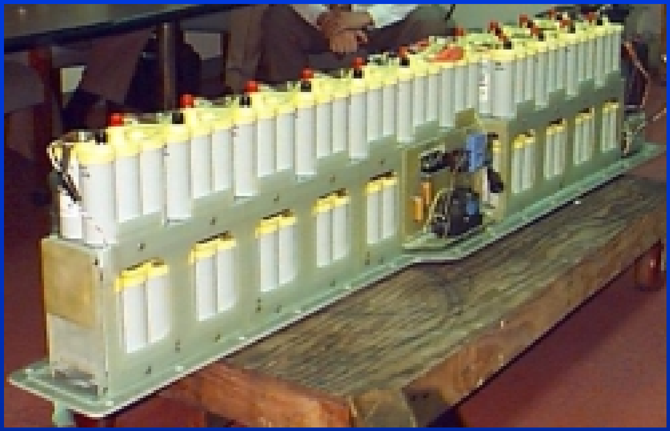
For high temperature batteries such as ZEBRA and lithium metal polymer has always been considered.

For room temperature batteries:

- From desirable to must by both vehicle OEMs and battery manufacturers
- From simple to complex/effective
  - active rather than passive
  - parallel rather series air cooling
  - use of liquid as cooling medium
- From pack thermal design to module thermal design

Battery Thermal Management System

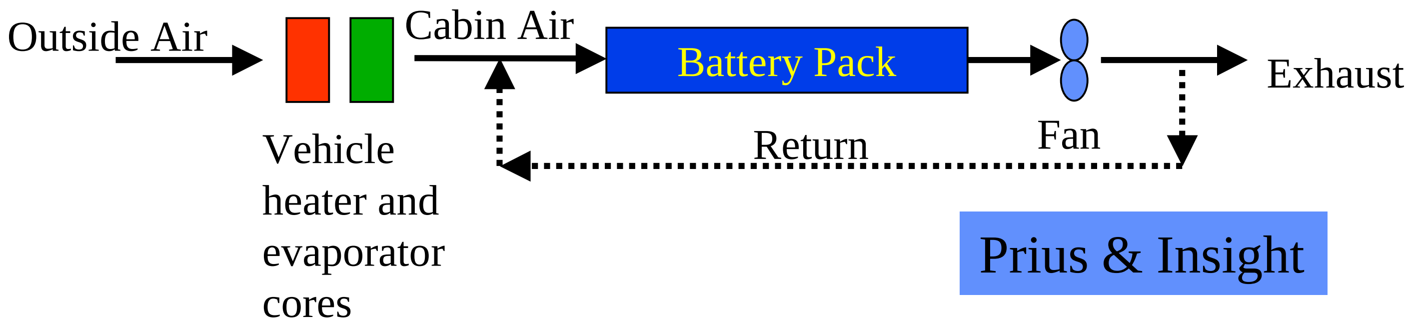
- Desired attributes
  - Small temperature variation within a module and within a pack
  - Optimum temperature range for all modules
- Requirements
  - Compact, lightweight, and easily packaged
  - Reliable and serviceable
  - Low-cost and low parasitic power



Thermal Control using Air Ventilation

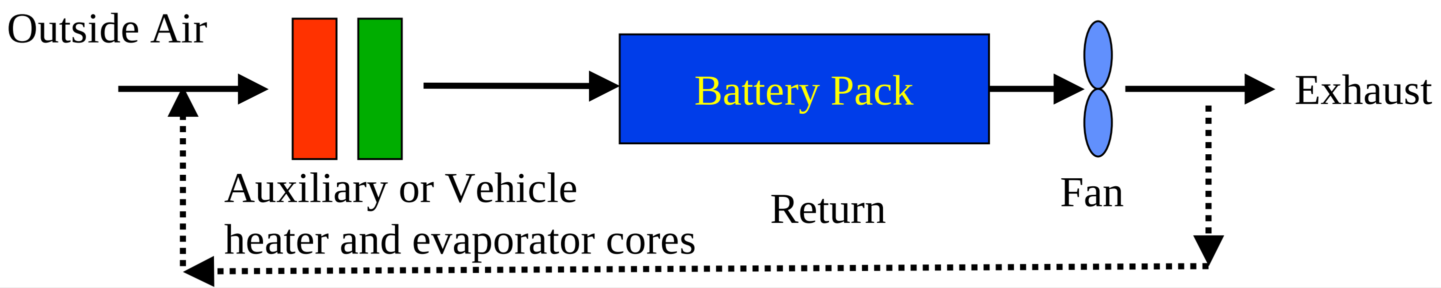
Passive cooling- Outside Air Ventilation

Passive heating/cooling- Cabin Air Ventilation

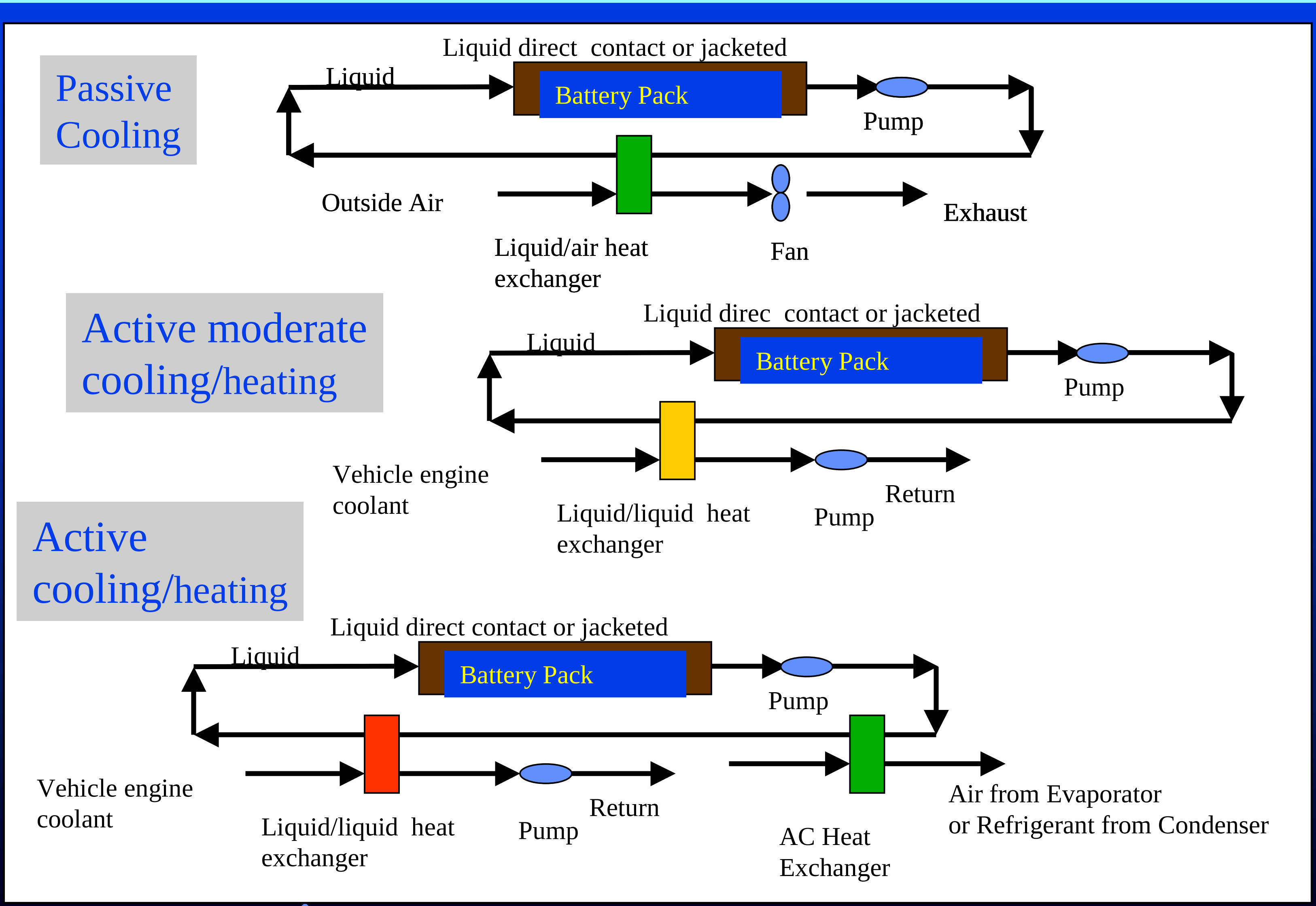


Prius & Insight

Active heating/cooling- Outside or Cabin Air



Thermal Control using Liquid Circulation



Passive Cooling

Liquid direct contact or jacketed

Liquid

Battery Pack

Pump

Outside Air

Exhaust

Liquid/air heat exchanger

Fan

Active moderate cooling/heating

Liquid direc contact or jacketed

Liquid

Battery Pack

Pump

Vehicle engine coolant

Liquid/liquid heat exchanger

Pump

Return

Active cooling/heating

Liquid direct contact or jacketed

Liquid

Battery Pack

Pump

Vehicle engine coolant

Liquid/liquid heat exchanger

Pump

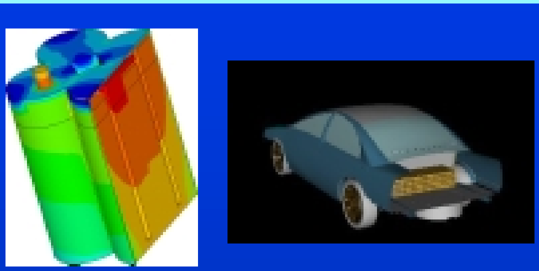
Return

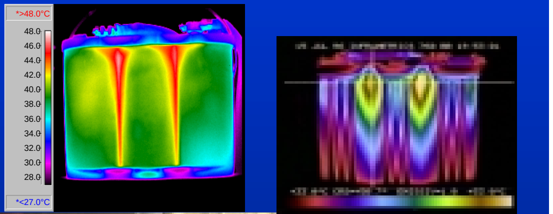
AC Heat Exchanger

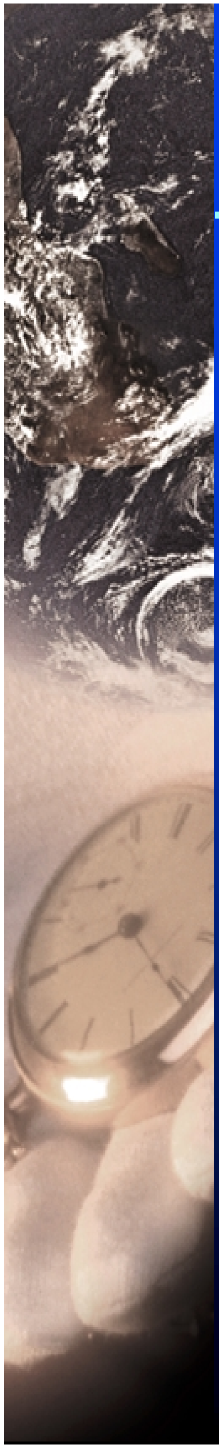
Air from Evaporator or Refrigerant from Condenser

NREL has used various tools in working with vehicle and battery manufacturers on BTM

- Thermal analysis (CAD) for proper design, evaluation, and packaging
- Thermal imaging for evaluation and diagnostics
- Fluid and heat transfer experiments for uniform temperature distribution and low parasitic power designs
- Thermal characterization for heat generation and heat capacity
- Battery modeling for vehicle simulation
- Battery Pack and Vehicle Testing





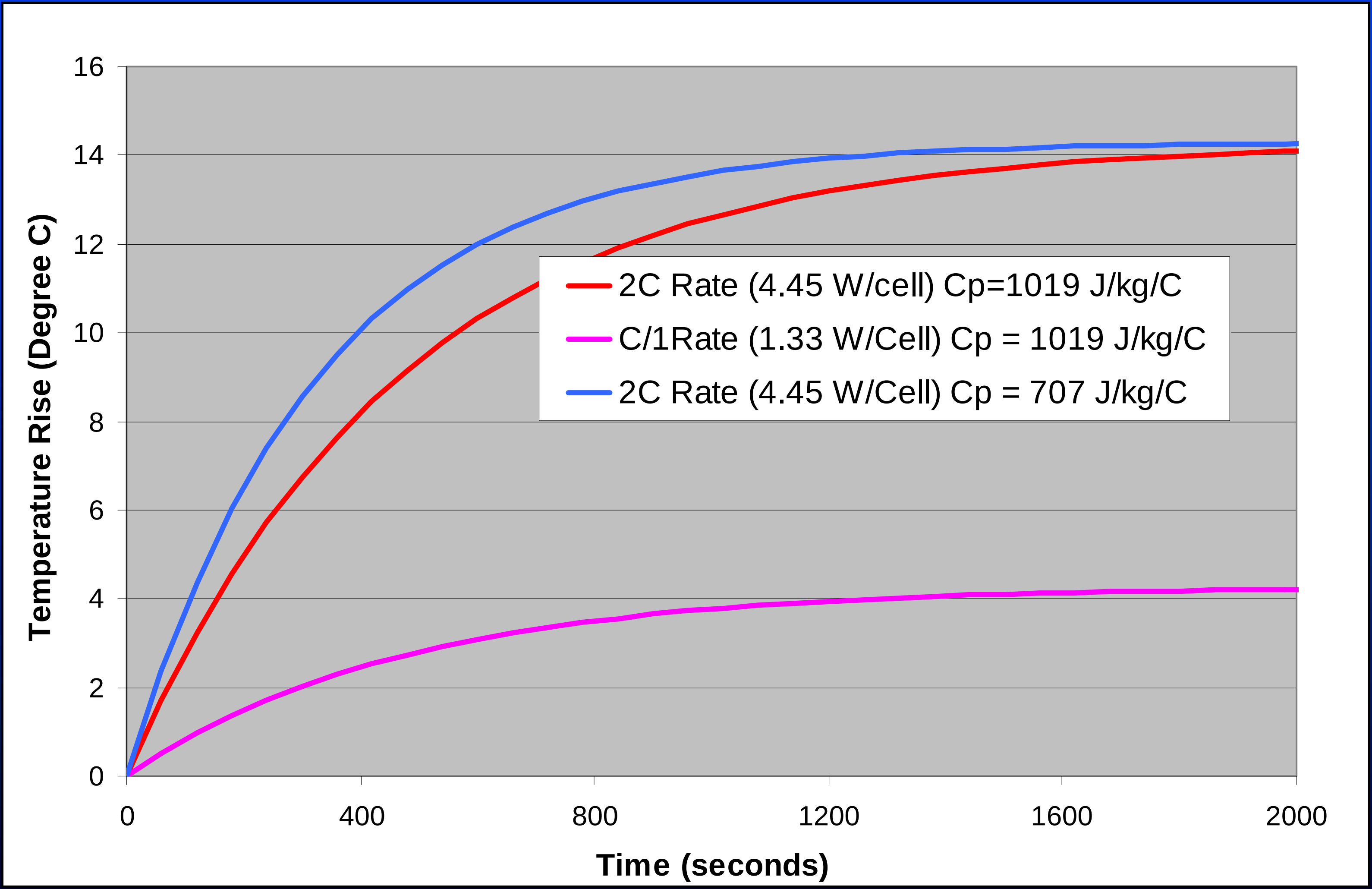


A Systematic Approach for Designing BTMS

- Define BTMS design objectives and constraints
- Obtain module heat generation and heat capacity
- Perform a first order BTMS evaluation
- Predict battery module and pack behavior
- Design a preliminary BTMS
- Build and test the BTMS
- Refine and optimize BTMS

Good pack thermal design starts with good module thermal design.

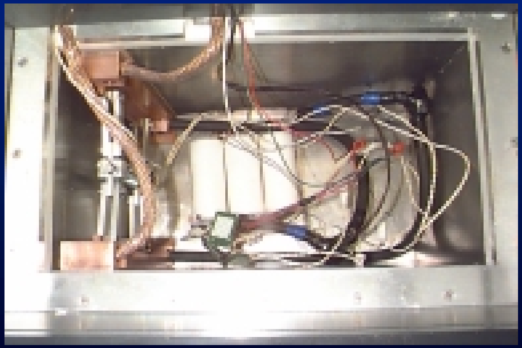
Heat Generation Rate and Heat Capacity Impacts Module Temperature Rise



Battery Calorimeter for Thermal Characterization

- We use a single-ended, large conduction calorimeter to measure **heat generation** at various rates, Temp, and SOC and **heat capacity**

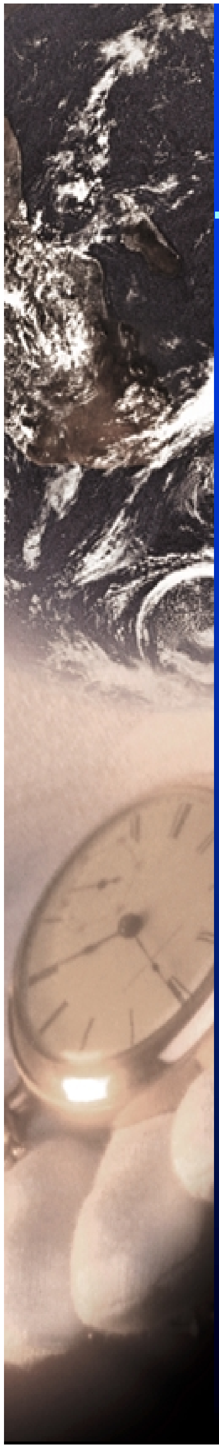
- Cavity dimensions: 21 cm x 20 cm x 39 cm (WxHxL)
- Heat rate detection: 0.015 W to 100 W
- Minimum detectable heat effect: 15 J (at 25ºC)
- Baseline stability: ± 10 mW
- Temperature range: -30ºC to 60ºC (±0.001°C)



Calorimeter Cavity

Typical Heat Capacity of EV/HEV Batteries

Battery type	Application	Average Temp (^{o}C)	Heat Capacity J/kg/^{o}C
NiMH - P	HEV	33.2	677.4
Li-Ion	HEV	33.1	795
Li-Ion Polymer	EV	18	1011.8
NiMH	EV	33.9	787.5
NiMH - C	HEV	19	810
VRLA	HEV	32	660
Ni-Zn	EV	19.95	1167



Heat Generation Rate Depends on SOC

Heat generation increases with higher rates.

Heat generation increases with lower temperature.

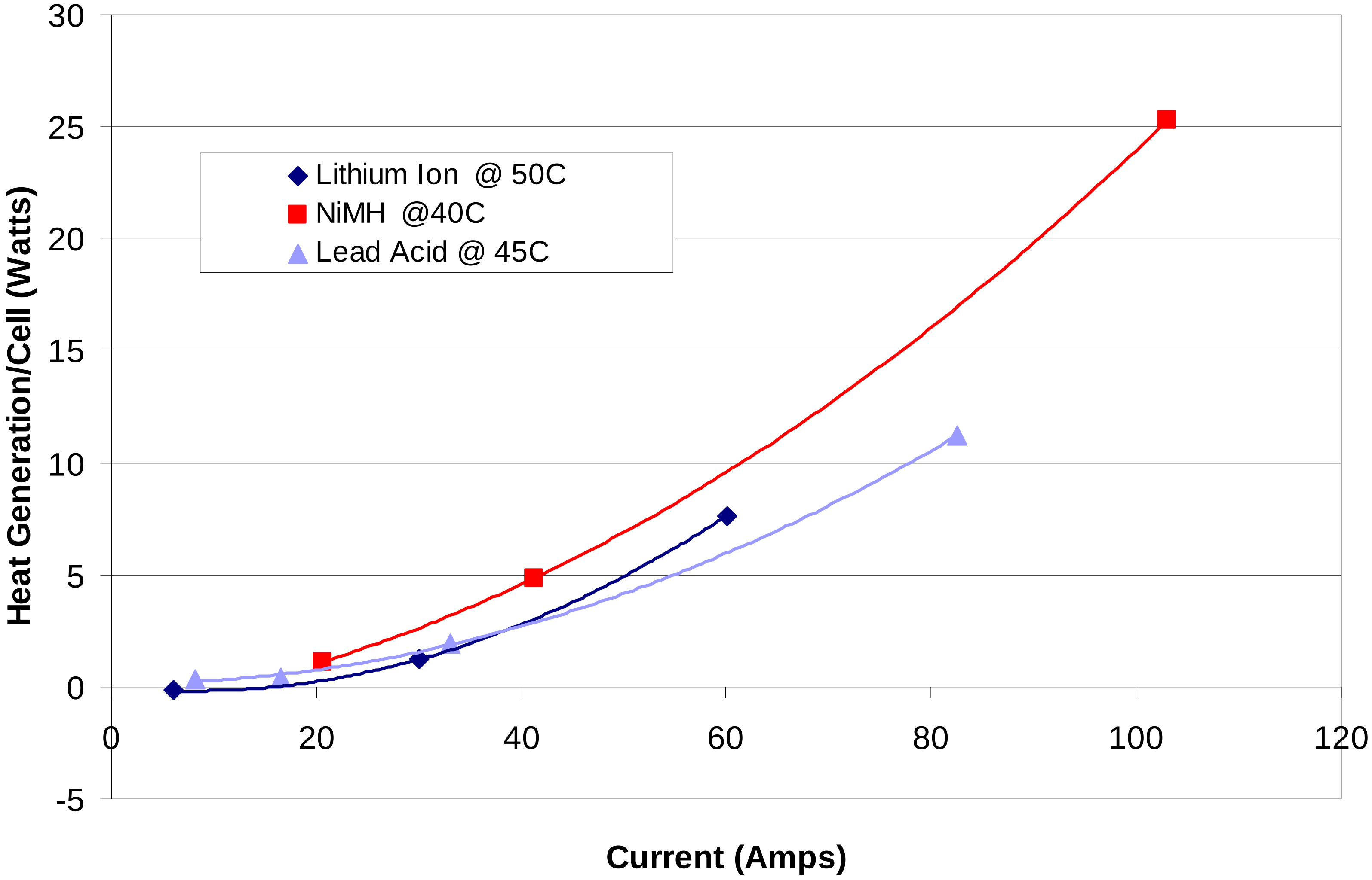
		Heat Generation (W)/Cell		
Battery Type	**Cycle**	**0°C**	**22-25°C**	**40-50°C**
VRLA, 16.5 Ah	C/1 Discharge, 100% to 0% State of Charge	1.21	1.28	0.4
VRLA, 16.5 Ah	5C Discharge, 100% to 0% State of Charge	16.07	14.02	11.17
NiMH, 20 Ah	C/1 Discharge, 70% to 35% State of Charge	-	1.19	1.11
NiMH, 20 Ah	5C Discharge, 70% to 35% State of Charge	-	22.79	25.27
Li-Ion, 6 Ah	C/1 Discharge, 80% to 50% State of Charge	0.6	0.04	-0.18
Li-Ion, 6 Ah	5C Discharge, 80% to 50% State of Charge	12.07	3.50	1.22

Heat Generation Rate Depends on SOC

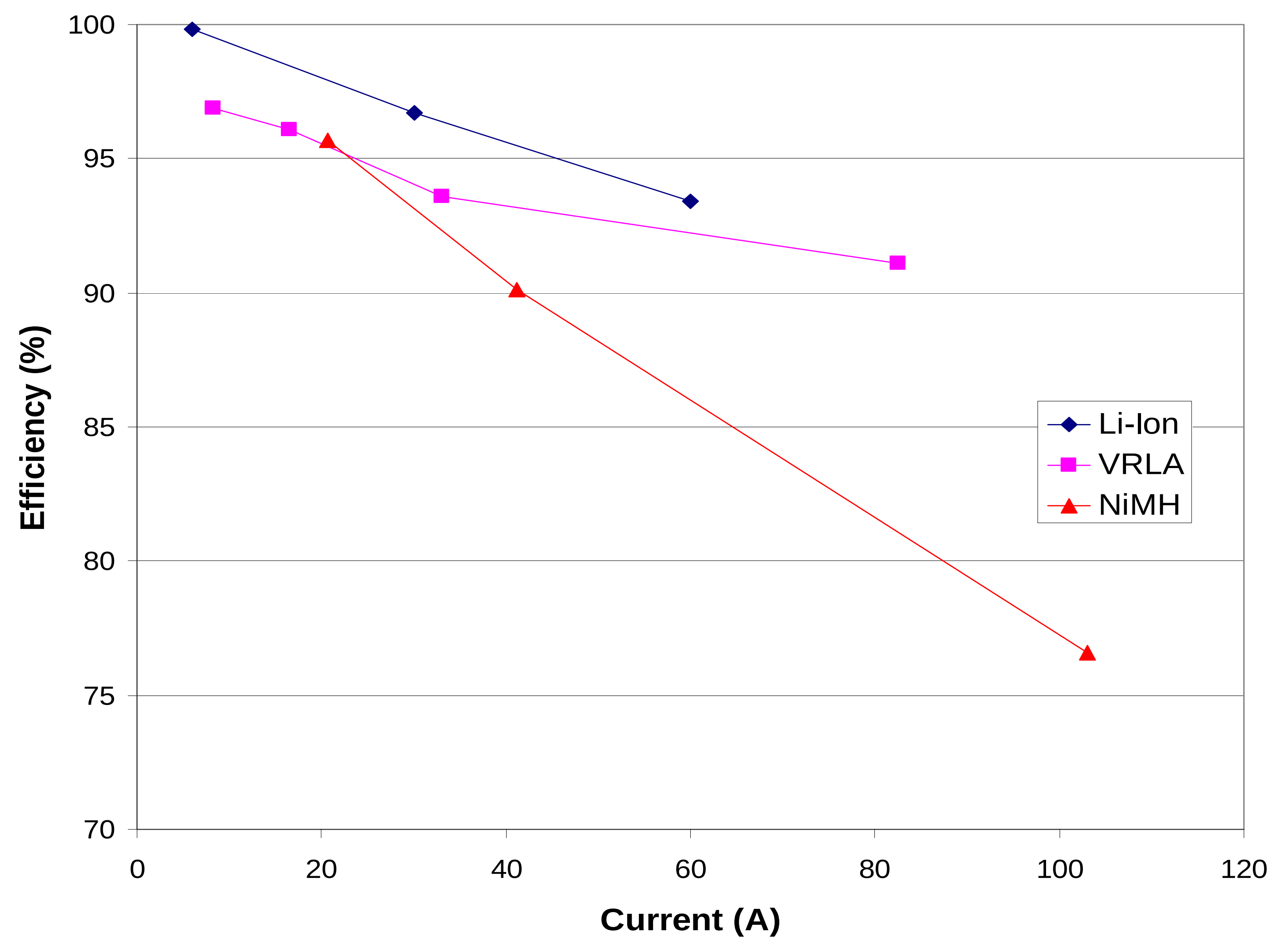
Heat generation increases with higher rates.
Heat generation increases with lower temperature.

		Heat Generation (W)/Cell		
Battery Type	**Cycle**	**0°C**	**22-25°C**	**40-50°C**
VRLA, 16.5 Ah	C/1 Discharge, 100% to 0% State of Charge	1.21	1.28	0.4
VRLA, 16.5 Ah	5C Discharge, 100% to 0% State of Charge	16.07	14.02	11.17
NiMH, 20 Ah	C/1 Discharge, 70% to 35% State of Charge	-	1.19	1.11
NiMH, 20 Ah	5C Discharge, 70% to 35% State of Charge	-	22.79	25.27
Li-Ion, 6 Ah	C/1 Discharge, 80% to 50% State of Charge	0.6	0.04	-0.18
Li-Ion, 6 Ah	5C Discharge, 80% to 50% State of Charge	12.07	3.50	1.22

Discharge Heat Generation at Elevated Temperatures for three HEV Batteries



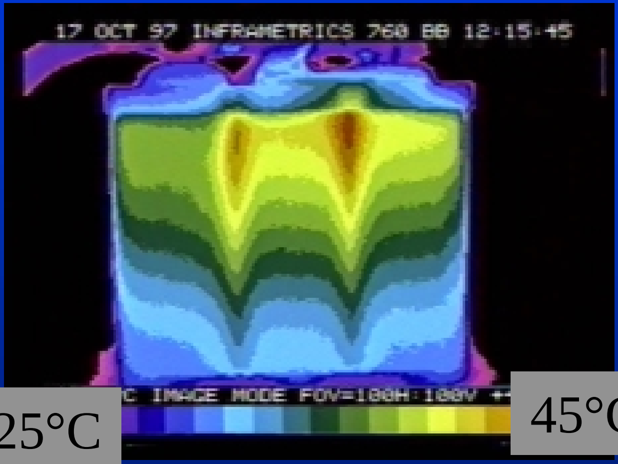
Discharge Energy Efficiency at Room Temperature



Temperature Distribution is Dictated by Module/Cell Design

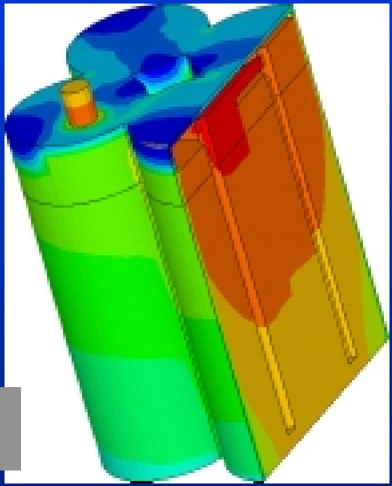
Factors: aspect ratio, # of cells, geometry, thermal conductivity, location of terminals, current density

Case 1

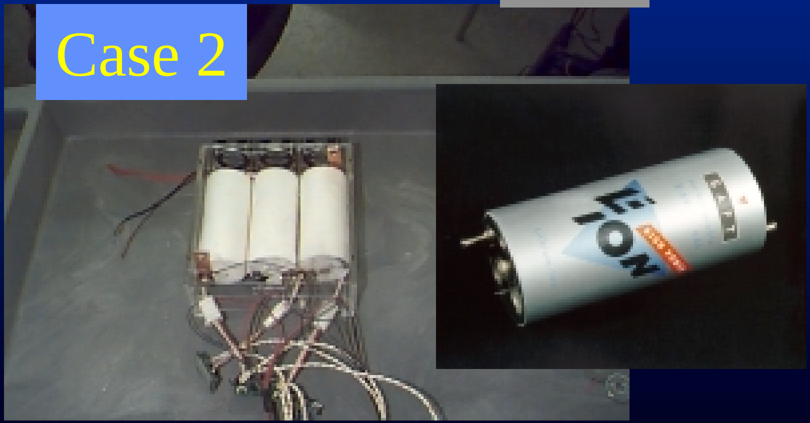


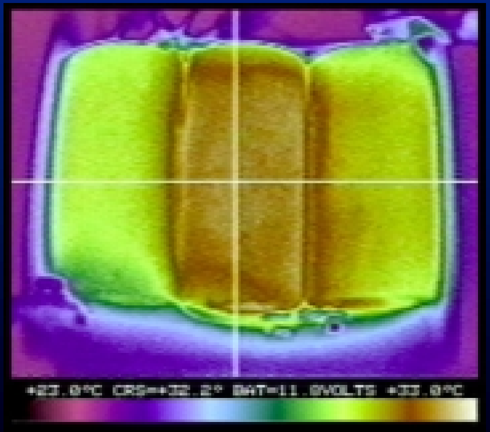
25°C

45°C



Case 2



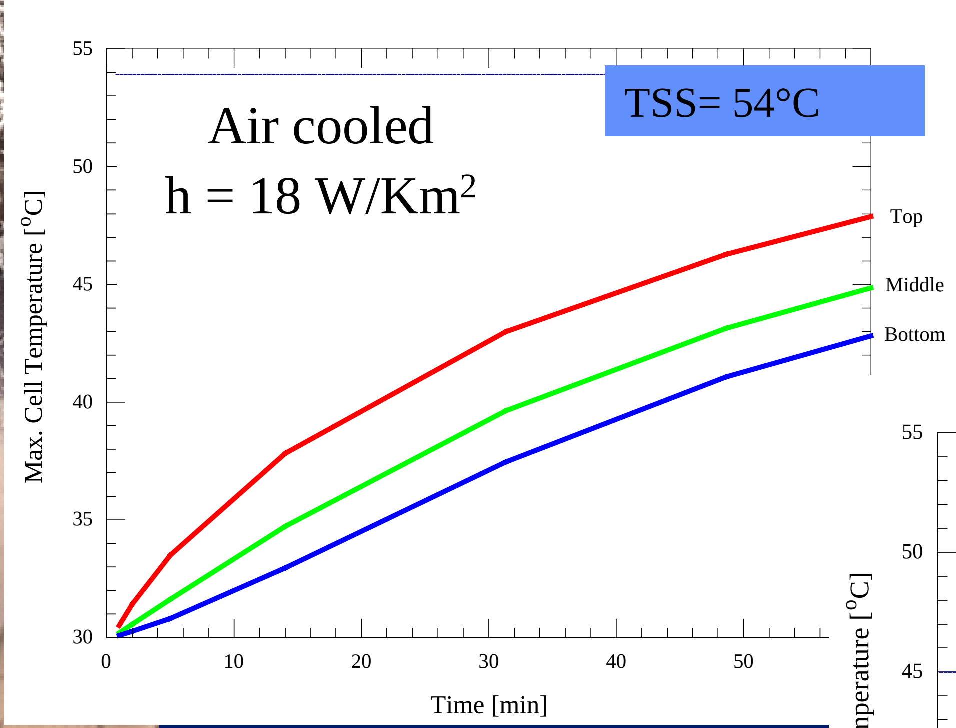


Only 2°C Difference

Air Cooling vs. Liquid Cooling

- Air
  - Ducting air
  - Direct contact
  - Simple designs
  - Less effective heat transfer
- Liquid
  - Piping liquid
  - Direct contact - oils
  - Indirect contact - water/glycol
  - Higher heat transfer rate

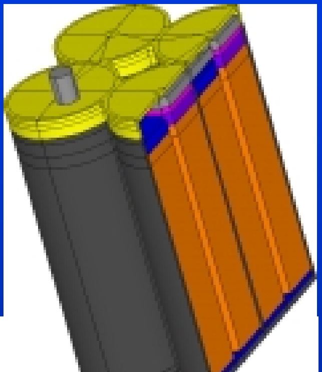
Air Cooling vs. Liquid Cooling - VRLA Module

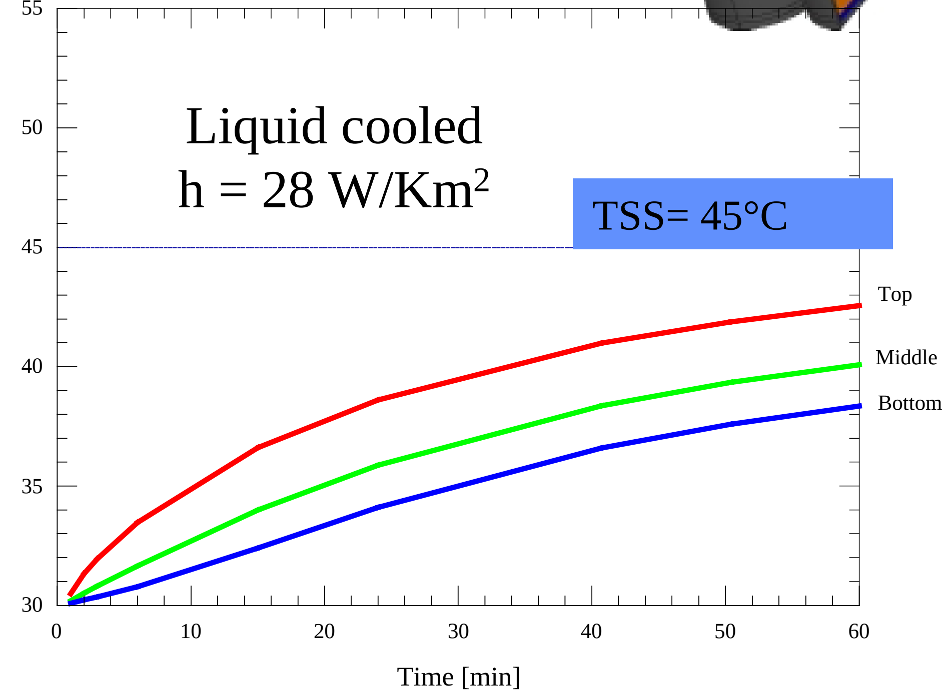


Air cooled
h = 18 W/Km^2

TSS= 54°C

Based on the same parasitic power





Liquid cooled
h = 28 W/Km^2

TSS= 45°C

Liquid cooling more effective

Air Cooling vs. Liquid Cooling

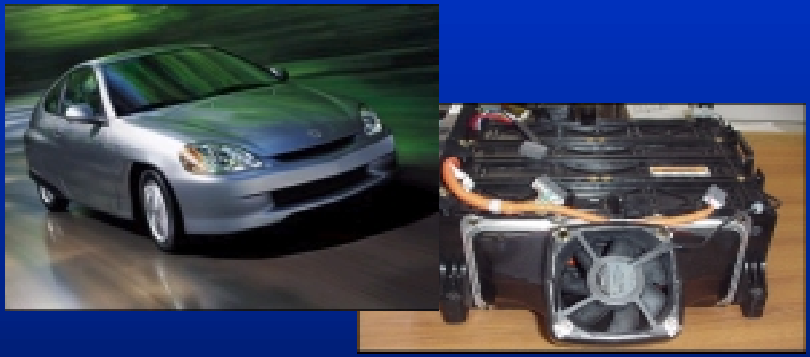
- Air
  - Ducting air
  - Direct contact
  - Simple designs
  - Less effective heat transfer
  - Lower volume efficiency
  - Lower cost
  - Easier maintenance
  - Not easily sealed from environment
  - Location sensitive
- Liquid
  - Piping liquid
  - Direct contact - oils
  - Indirect contact - water/glycol
  - Higher heat transfer rate
  - Compact design
  - More parts
  - Higher maintenance
  - Higher cost
  - Could be sealed easier
  - Location insensitive
  - High viscosity and thermal mass at cold temperatures

Liquid Cooled Modules

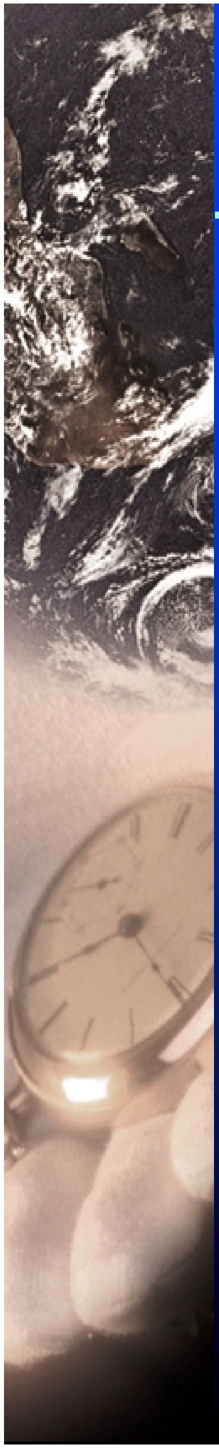
Integrated liquid cooling in a module provide an opportunity to reduce temperature distribution in addition to lowering the overall temperature for large modules, good for electrical balancing.

Active vs. Passive Systems

- Passive systems less complicated
- Passive systems have lower cost and lower number of components



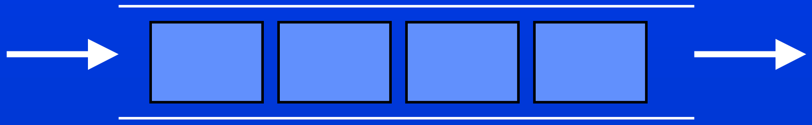
- Passive systems consume less energy
- Passive systems not adequate at all climates
- With maturing of HEVs, more battery thermal management systems will use active systems

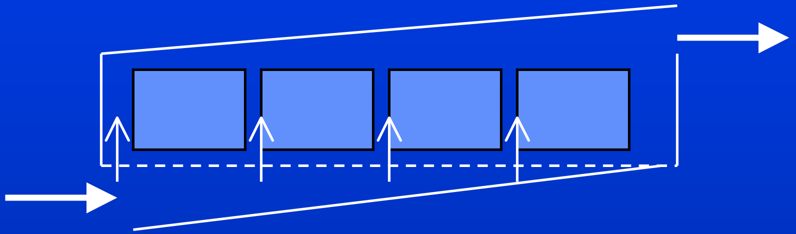


Cooling only vs. Cooling/Heating Systems

- Cooling only systems work fine for moderate climates such as California.
- Utilizing engine coolant can provide some cooling for warm days and heating for cool days, but has limitations.
- HEVs and EVs operating for all climates (-30 to 60°C) need both active battery heating and cooling
- Cooling can be provided by vehicle/auxiliary Air Conditioner components
- For cold starts, a heating source may not be available so the battery may need to be used for self heating
- Use of active systems can reduce fuel economy.

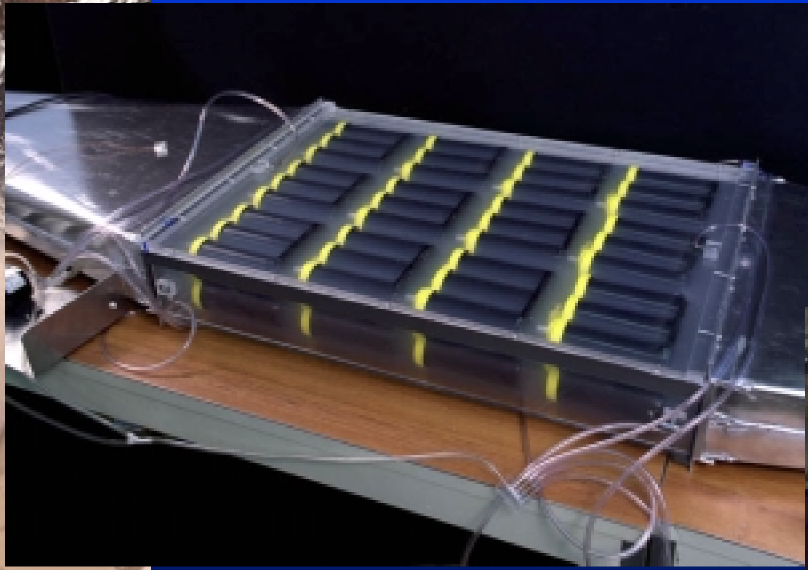
Series vs. Parallel Air Distribution





Air

Balancing pressure drops with proper manifold



Series flow

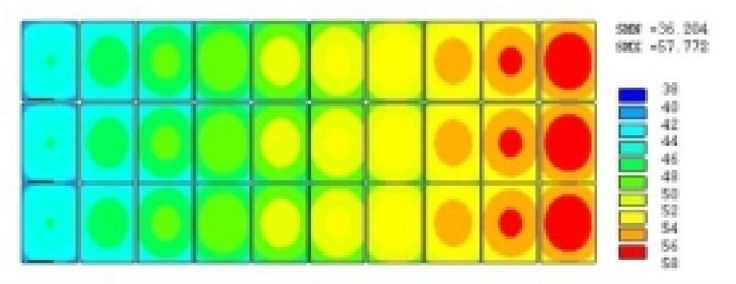
In this case, modules on side airflow across

Parallel flow

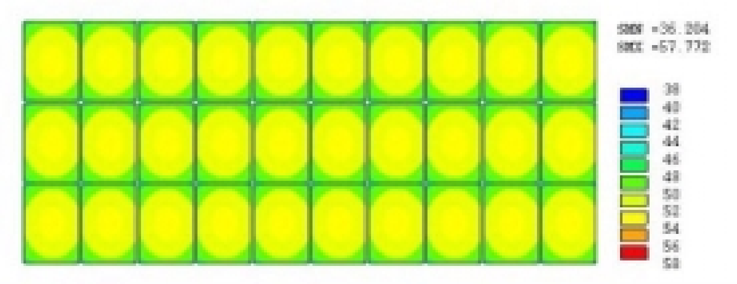
In this case modules upright airflow up

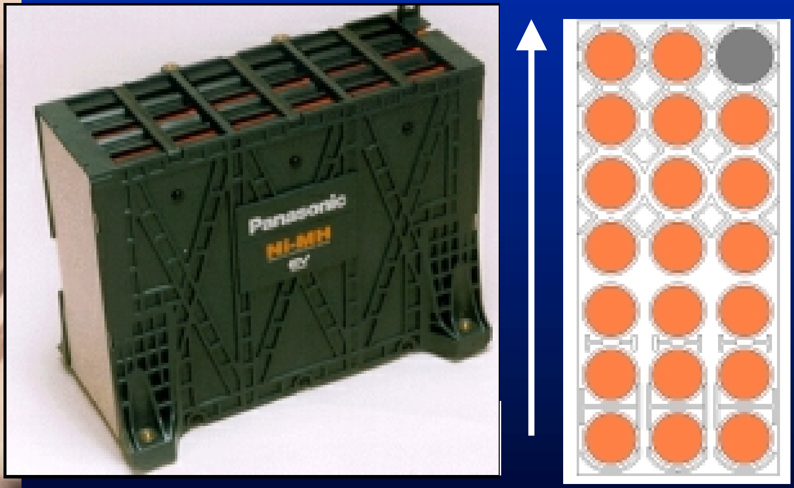
Parallel flows provides a better temperature distribution

Series air flow

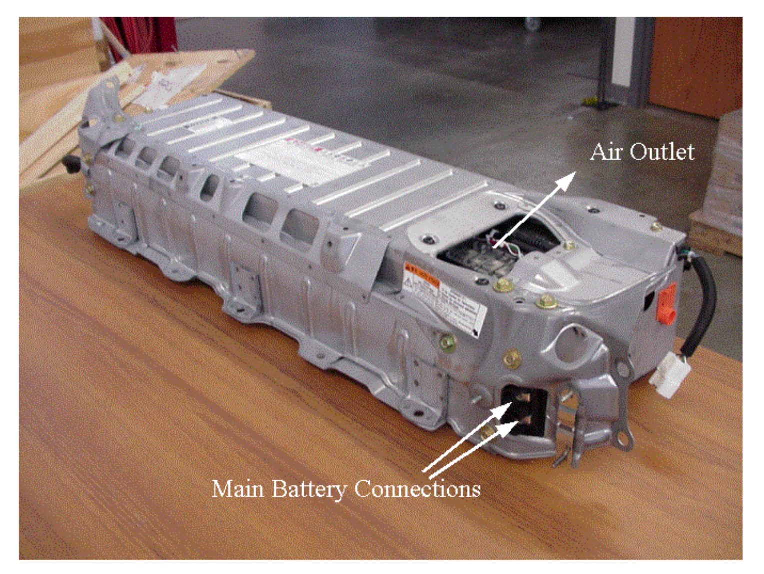


Parallel air flow

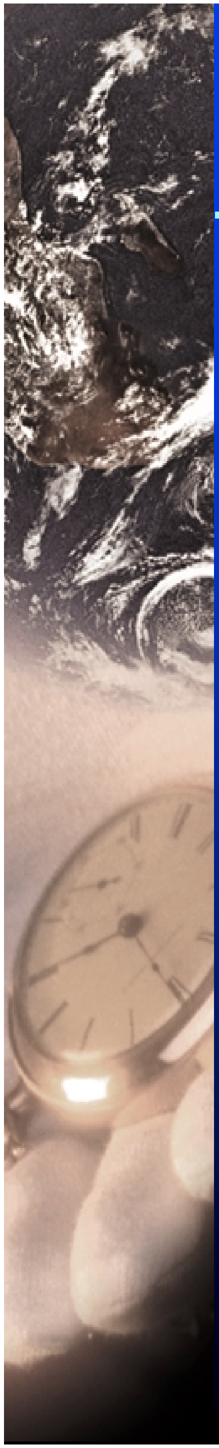




Japan Prius and Insight

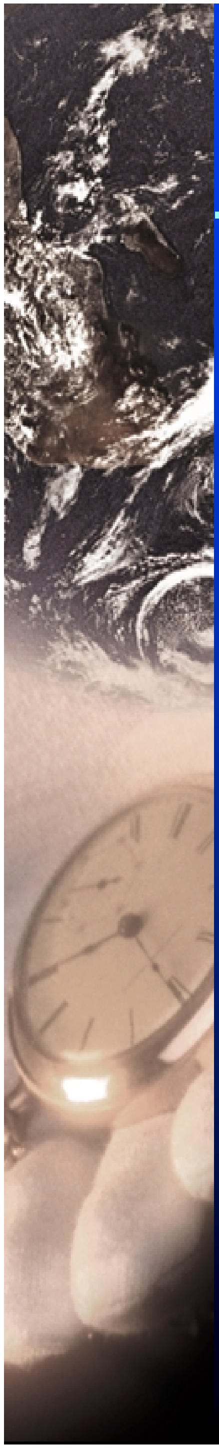


New Prius



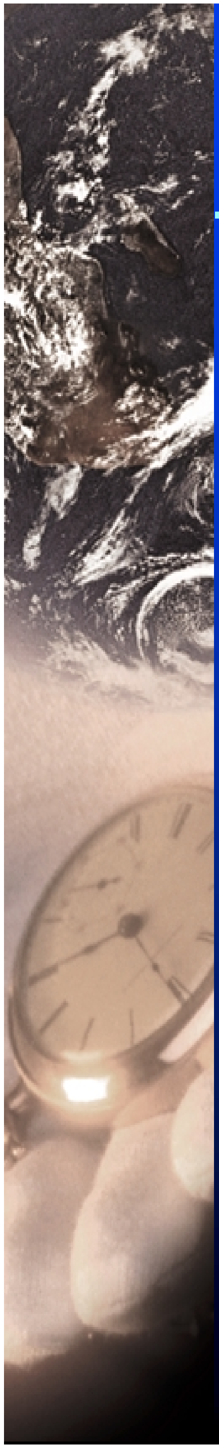
Thermal Management of VRLA, NiMH, and Li-Ion

- Factors that determine magnitude of thermal management system
  - Heat generation rate
  - Energy efficiency
  - Sensitivity to temperature
  - Cold and hot performance and life
- NiMH less efficient and generates more heat and appear to be more sensitive to temperature variation. So NIMH needs a more elaborate thermal management system.
- Li-Ion generates more heat in a smaller volume and is more sensitive to extreme cold and hot, so also need a complete battery management system



Concluding Remarks

- Thermal management of HEV batteries are becoming more sophisticated.
- Liquid cooling more effective, but more complex
- Air cooling for power-assist HEVs is sufficient.
- Liquid cooling may be needed for EV and series HEVs
- Parallel air flow distribution more desirable.
- NiMH requires more elaborate thermal management, than Li-Ion than VRLA
- Location of pack has a strong impact on type of cooling system (air vs.liquid).
- Active systems will be required, and heating will be a challenge



Acknowledgments

This work was supported by of U.S. Department of Energy, Office of Advanced Automotive Technologies.

www.ctts.nrel.gov/BTM

Contributions by Battery Thermal Management Team
Matt Keyser
Mark Mihalic
Matthew Zolot