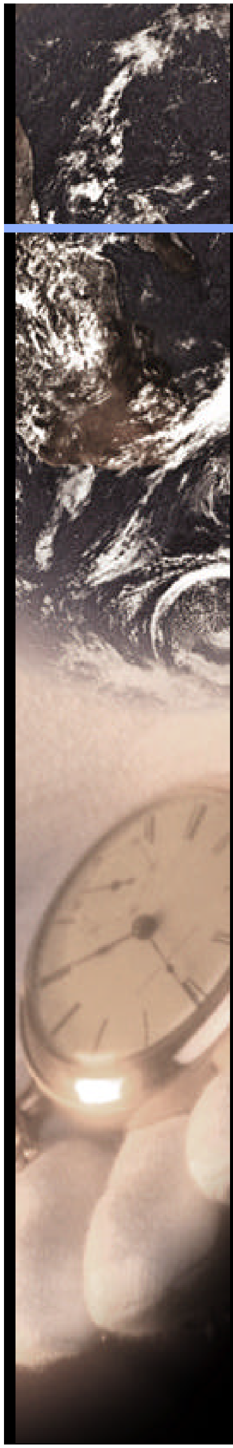

An Approach for Designing Thermal Management Systems for EV and HEV Battery Packs

4th Vehicle Thermal Management Systems Conference

London, UK

May 24-27, 1999

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CENTER FOR TRANSPORTATION TECHNOLOGIES AND SYSTEMS

Working with Industry

This work was sponsored by the U.S. Department of Energy as part of the cost-shared Hybrid Vehicle Propulsion Systems Program.

GM

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

Ford

OPTIMA BATTERIES

JOHNSON CONTROLS

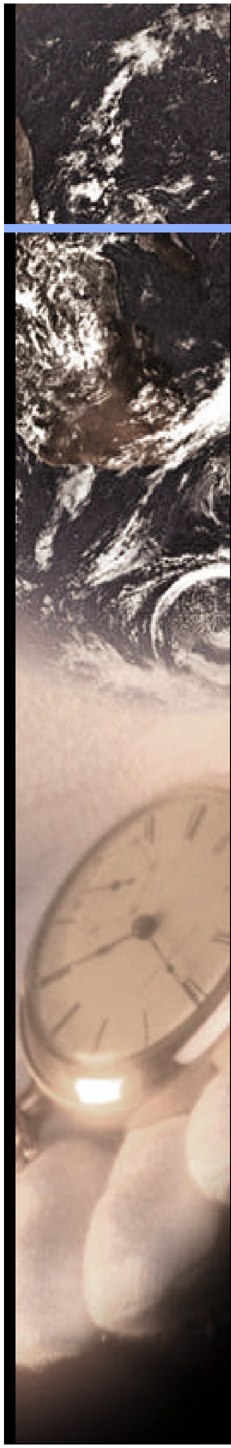
AeroVironment

GNB TECHNOLOGIES

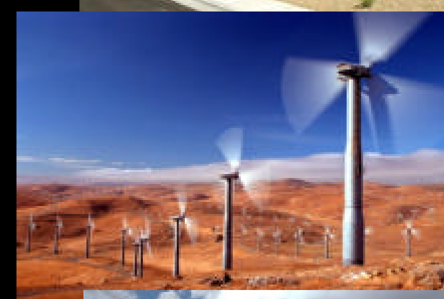
DAIMLERCHRYSLER

Presentation Outline

- Background
- Why battery thermal management system (BTMS)?
- Design approach for BTMS
- Results and discussion for a battery type
- Concluding remarks



National Renewable Energy Laboratory



- NREL is one of the eleven U.S. Department of Energy's national laboratories
- NREL's mission is to develop and promote renewable energy and energy efficient technologies in various sectors
- NREL's transportation activities are focused on alternative fuels, emissions, and HEV components and systems

Electric/Hybrid Vehicles for 21st Century Transportation

- Reduced emissions and pollution
- Improved fuel economy


Ford P2000 HEV

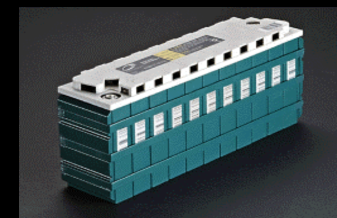

Toyota Prius


Audi Duo HEV

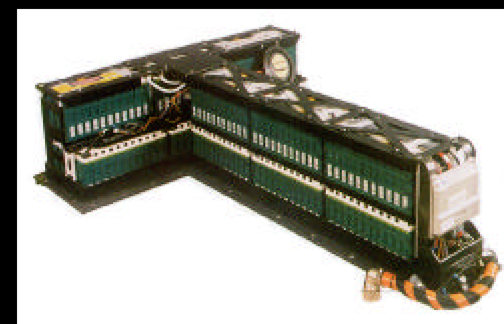

GM Series HEV


Peugeot EV

Battery Temperature is Important



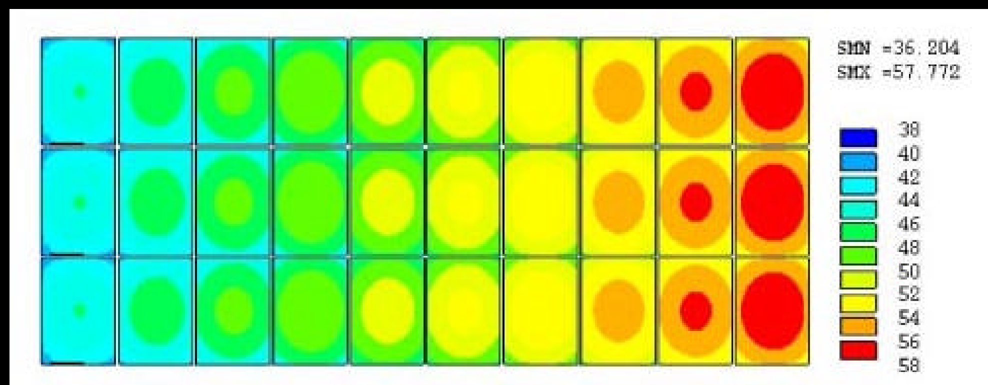
- Temperature affects battery
  - Operation of the cells/modules
  - Round trip efficiency and charge acceptance
  - Power and energy
  - Safety and reliability
  - Life and life cycle cost



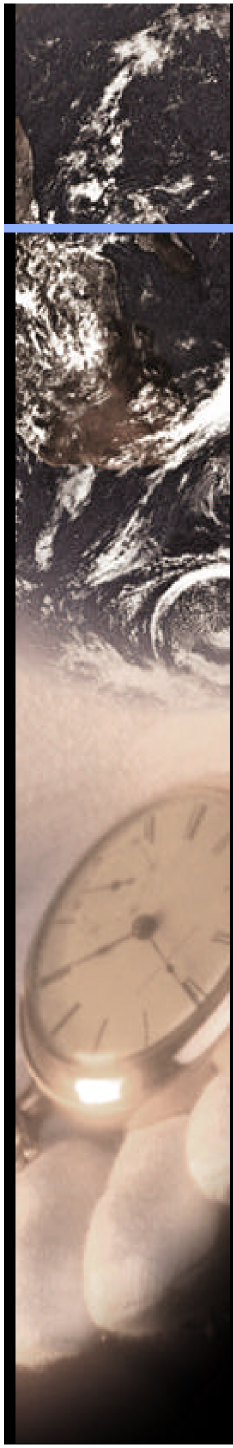
Battery temperature affects vehicle performance, reliability, safety, and life cycle cost

Thermal Management is Needed

- Regulate pack so it operates in the desired temperature range for optimum performance/life



- Reduce uneven temperature distribution in a pack to avoid unbalanced modules/pack to avoid reduced performance
- Eliminate potential hazard related to uncontrolled temperature



Functions of Thermal Management

- Maintain battery pack temperature (heating/cooling) using
  - air
  - liquid (direct and indirect)
  - insulation
  - phase change material
  - passive (ambient) or active (HX, heaters, A/C)
  - combination of various approaches
- Provide ventilation for batteries that generate potentially hazardous gases
- Provide a control strategy for safe operation

Design of Thermal Management System

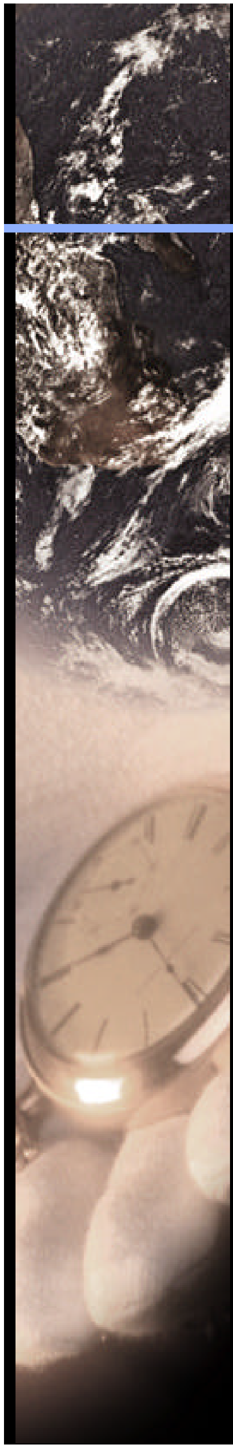
- NREL has been working with automobile and battery manufactures in evaluating and designing battery thermal management systems (BTMS)
  - Energy/thermal analysis
  - Thermal characterization
  - Fluid/heat transfer experiments
  - Battery testing

- We believe a systematic approach to design and evaluate battery modules and packs leads to better battery thermal management

A Systematic Approach for Designing BTMS

Major Steps:

1. Define BTMS design objectives and constraints
2. Obtain module heat generation and heat capacity
3. Perform a first order BTMS evaluation
4. Predict battery module and pack behavior
5. Design a preliminary BTMS
6. Build and test the BTMS
7. Refine and optimize BTMS



Define BTMS Design Objectives and Constraints

- Battery pack specifications
  - module type
  - number of modules
  - geometry
  - dimensions
  - preliminary lay out in vehicle
- Desired battery thermal performance
  - average operating temperature
  - acceptable module delta T
  - acceptable pack delta T
  - Safety constraints (e.g., need for ventilation)

Battery Pack Specifications

- Depends on the type of battery
  - Lead acid: 30 Wh/kg; 450 W/kg
  - NiMH: 60 Wh/kg; 200 W/kg
  - Li-Ion: 80 Wh/kg; 300 W/kg
- Depends on the type of vehicle
  - EV (80 kW, 28 modules)
  - Parallel HEV
    - Large engine (57 kW engine; 29 kW motor, 10 modules)
    - Small engine (30 kW engine; 46 kW motor, 16 modules)
  - Series HEV
    - Large engine (52 kW engine; 61 kW motor, 21 modules)
    - Small engine (33 kW engine; 70 kW motor, 24 modules)

Desired Thermal Performance

- Operating temperature depends on battery type
  - Lead acid: 0°C to 55°C (45°C)
  - NiMH: -10°C to 40°C (25°C)
  - Li-Ion: -20°C to 60°C (30°C)
- Acceptable temperature variation in module
  - Size dependent and type dependent
    - 2-3°C in small modules
    - 6-7°C in large modules
- Acceptable temperature variation in pack
  - Size and EV/HEV-type dependent
    - 2-3°C in small packs (parallel HEV)
    - 7-8°C in large packs (EV, series HEV)

Module Heat Generation

- Heat generated from a module depends on:
  - type of battery and its efficiency
  - Conditions (temperatures; state of charge)
  - Charge/discharge profile
- Heat generated could be:
  - Measured in a calorimeter
  - Estimated from electric energy balance

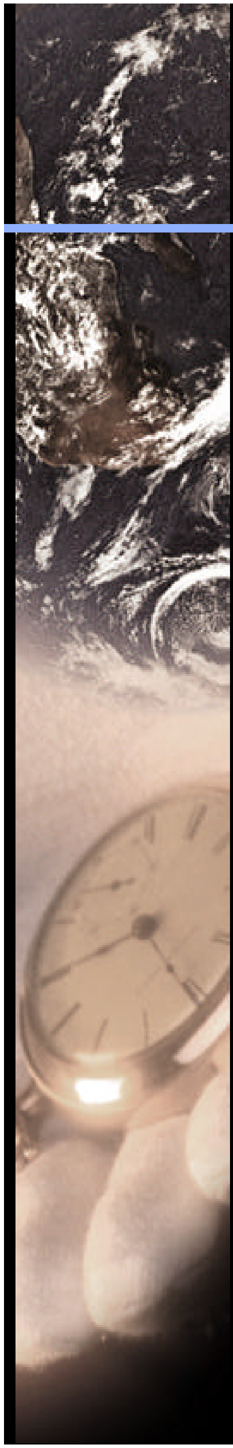
NREL Calorimeter

Data for a 12 V HEV module	Module Heat Generation (W)	
Cycle	25°C	40°C
16.5 A discharge, 80% to 20% SOC	7.7	2.1
16.5 A charge, 20% to 80% SOC	16.0	15.8
HEV 1.3 FUDS, initial SOC of 75%	46.0	36.8

Module Heat Capacity

- Module heat capacity depends on:
  - Battery type
  - Battery case
  - Conditions (T, SOC)
- Heat capacity could be:
  - Estimated based on mass-weighted average of components
  - Measured in a calorimeter

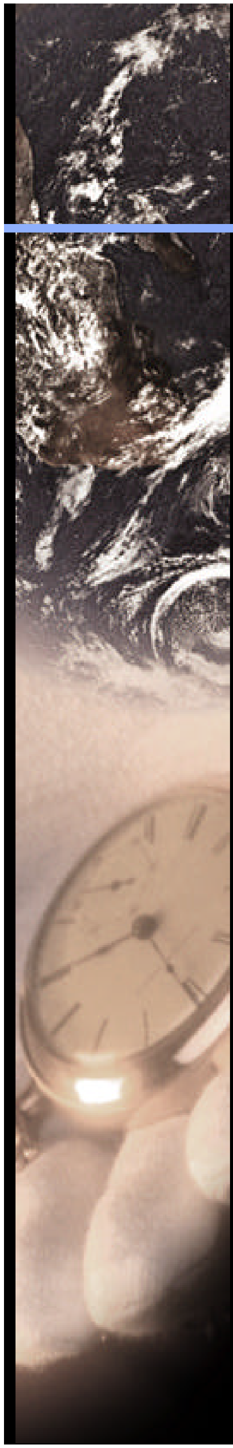
Optima 12V HEV Module
Specific heat = 640 J/kg/K
Density = 4035 kg/m^3



Perform a First Order BTMS Evaluation

- Perform energy and thermal analysis
  - steady state [$q_b = mr_f C_f (T_{fo} - T_{fi})$]
  - transient [$m_b C_b dT_b/dt = q_b = h A (T_b - T_f)$]
  - different heat transfer medium (air, liquid, PCM)
  - different flow paths (direct/indirect, series/parallel)
  - different flow rates and conditions
- Estimate of fan/pump parasitic power
- Preliminary selection of the heat transfer medium and associated flow rate

Is there a need for BTMS? What size and type?

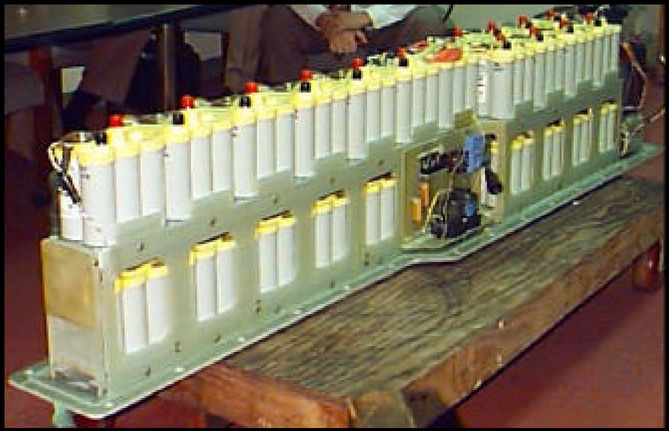


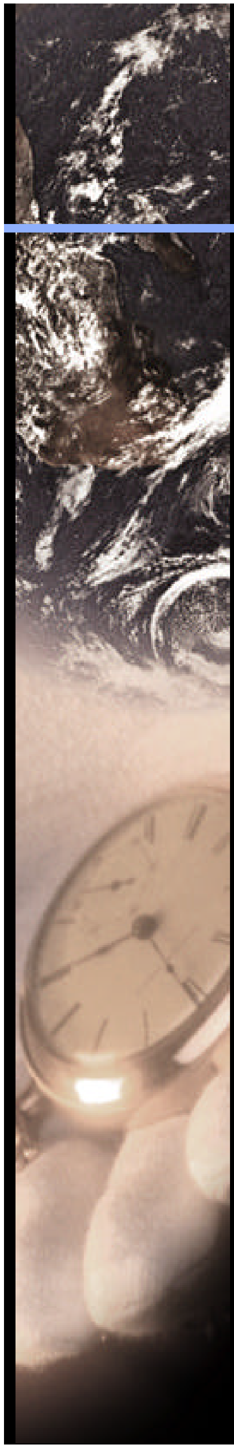
Design a Preliminary BTMS

- Conduct analyses and experiments to design
  - integrated pack thermal system
  - size auxiliary components (fan/pump, HX, heater, coil)
- Devise control strategy for operating BTMS
- Estimate cost
- Evaluate other factors (maintenance, ease of operation, reliability)
- Compare alternative BTMS and decide on one option

Build and Test the BTMS

- Build a battery pack with an integrated BTMS
- Conduct bench-top experiments to validate analysis
- Evaluate thermal control strategies
- Install a prototype pack/BTMS in a vehicle
- Evaluate using a vehicle dynamometer





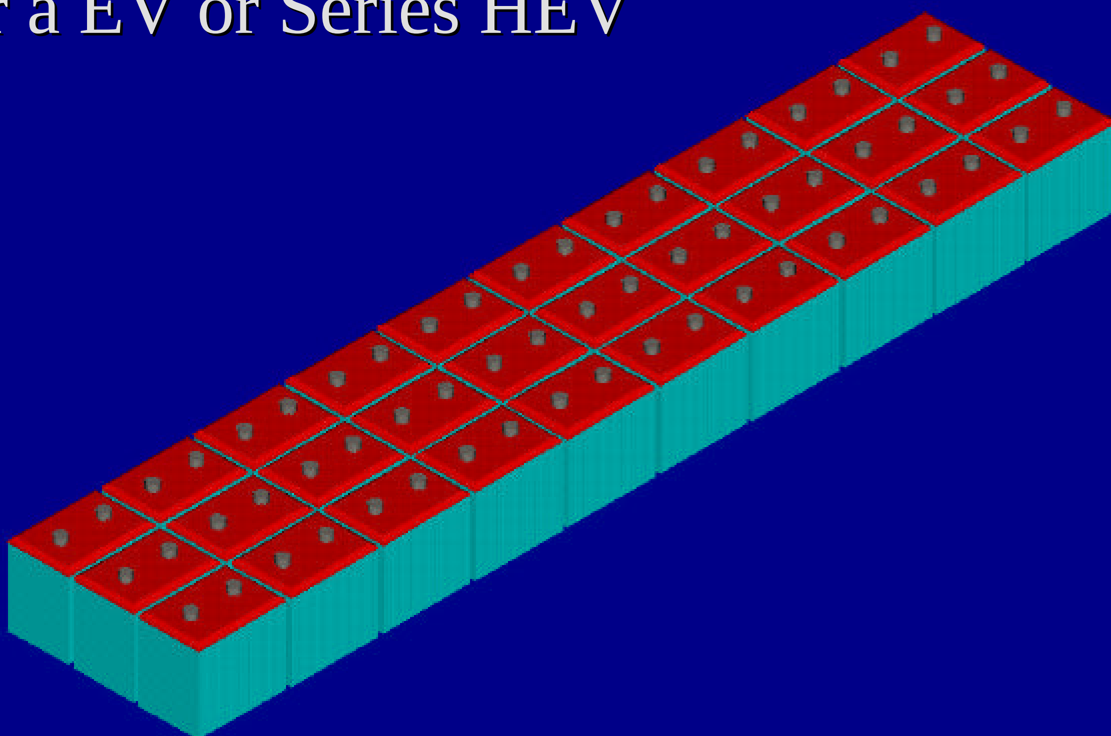
Refine and Optimize the BTMS

- Refine the analysis and design of the components and systems
- Repeat previous steps considering:
  - battery performance and life
  - impact on vehicle performance
  - cost
  - maintenance
  - reliability
- Finalize the optimum design

2-D Pack Thermal Analysis

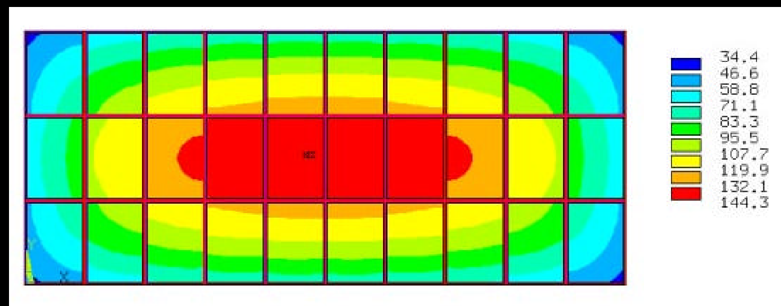
30 Modules

For a EV or Series HEV



Heat Generation: 35 W/module

Pack FEA thermal analysis predicts behavior of various designs



Closed, no flow

Tmax = 144ºC

Tmin =40ºC

Air entering at 25ºC

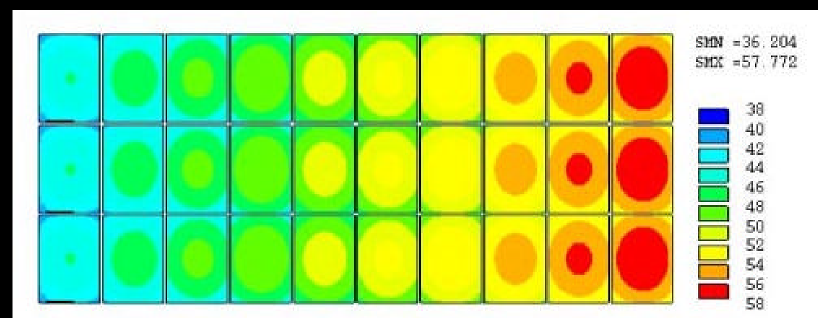
Air leaving at 38ºC

Open, series air flow

air flow: side to side

Tmax = 58ºC

Tmin =40ºC



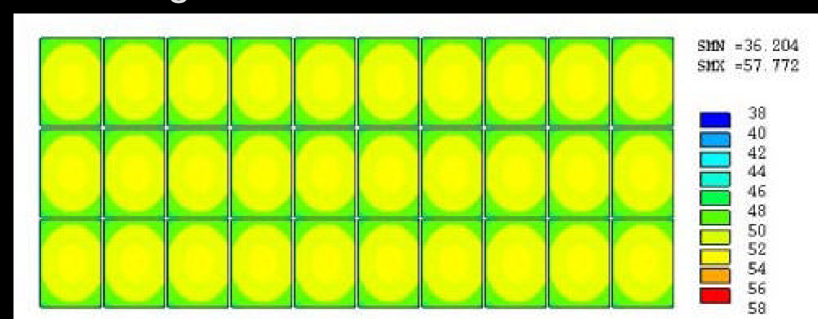
Air leaving at 38ºC

Open, parallel air flow

air flow: bottom to top

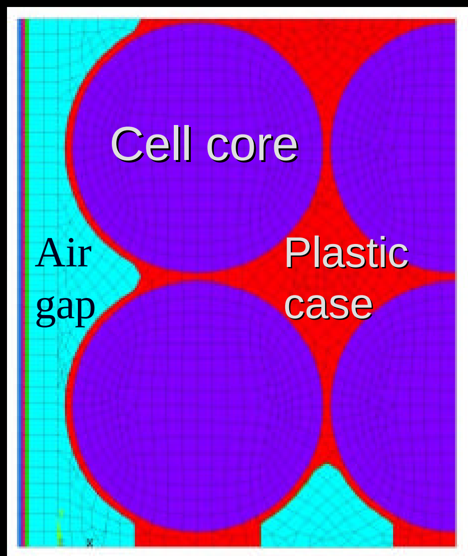
Tmax = 54ºC

Tmin = 46ºC



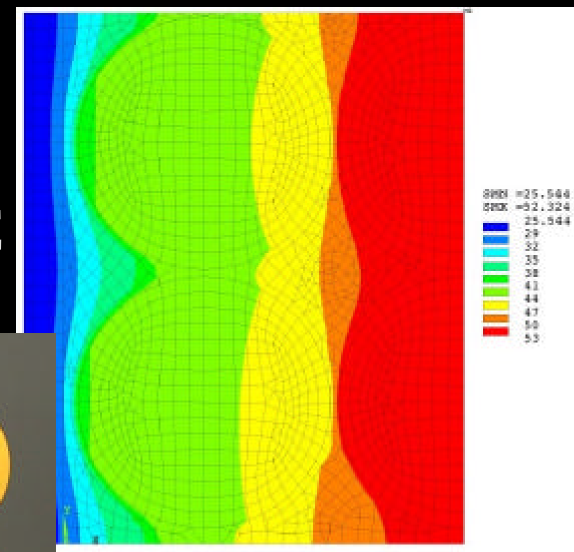
Air entering at 25ºC

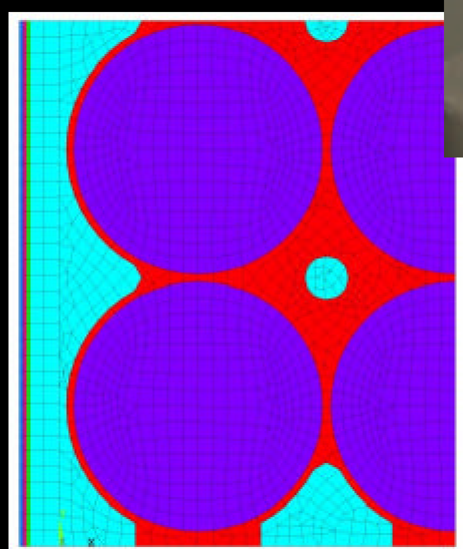
Analysis Indicated Thermal Improvement by Adding Cooling Holes



No Holes

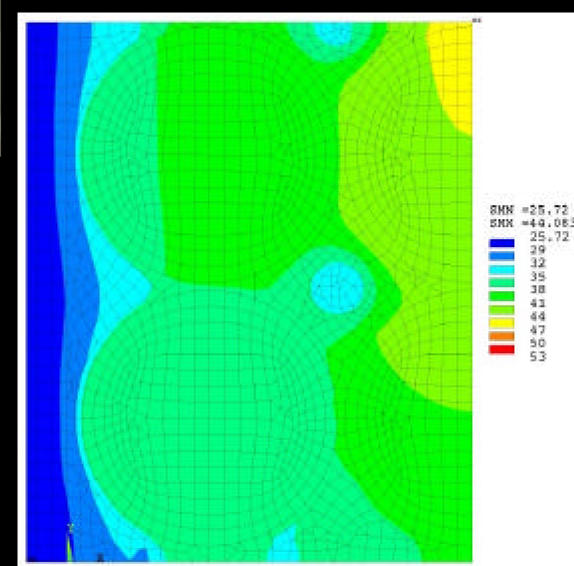
Tmax = 53ºC
Delta Tcore = 13ºC





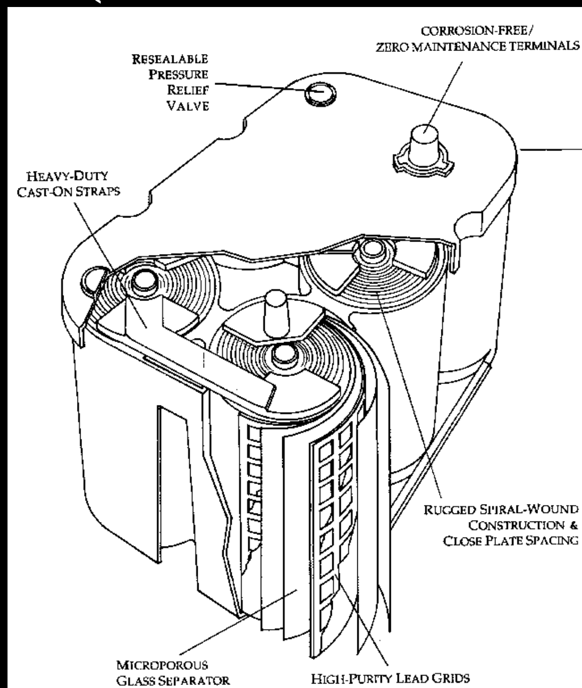
With Holes

Tmax = 44ºC
Delta Tcore = 9ºC



3-D Module Thermal Analysis

- Based on a prototype HEV module by Optima Batteries (Aurora, Colorado, USA)



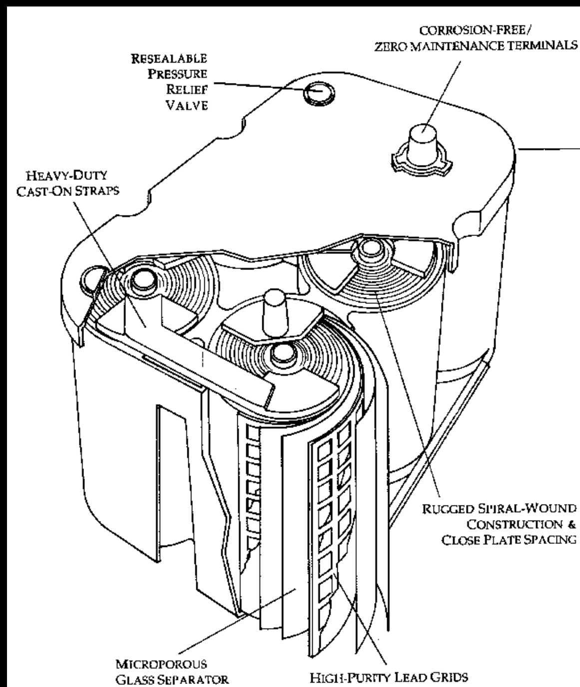
Valve regulated, lead acid

Spirally-wound cylindrical cells

6-cell modules (12 V, 16.5 Ahr, 2.9 kW, 6 kg)

Estimating Thermal Conductivity of Optima Cells

$$Q_x = k_x \Delta T / \Delta x$$



A section of cell with two lead grid

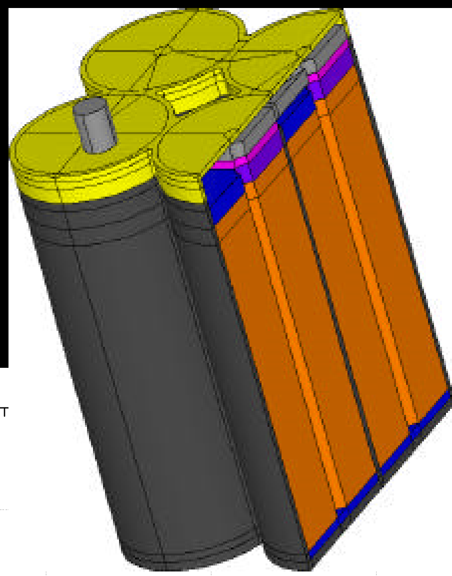
A section of cell with all cell elements

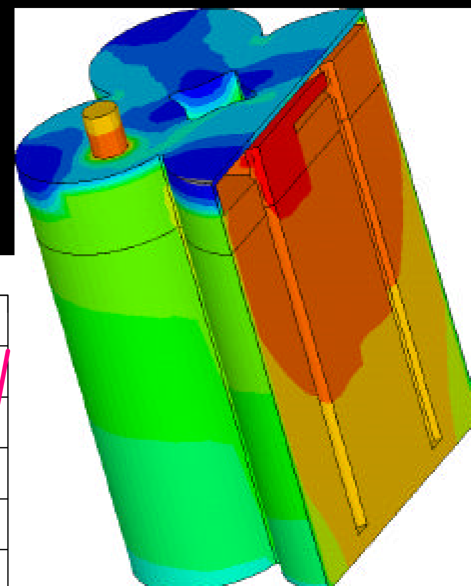
Apply known ΔT across two x planes
Find Q_x and calculate overall k_x

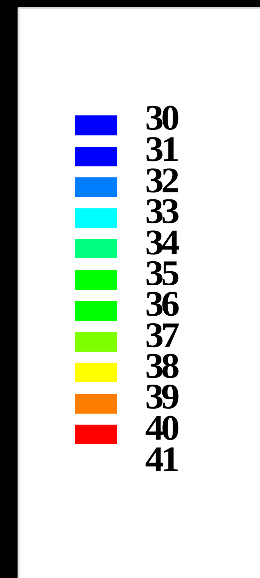
Axial:	**Ave: $k_{eff,a}$ = 9.5 W/mK**
Radial	**Ave: $k_{eff,r}$ = 6.6 W/mK**
Tangential:	**Ave: $k_{eff,t}$ = 8.8 W/mK**

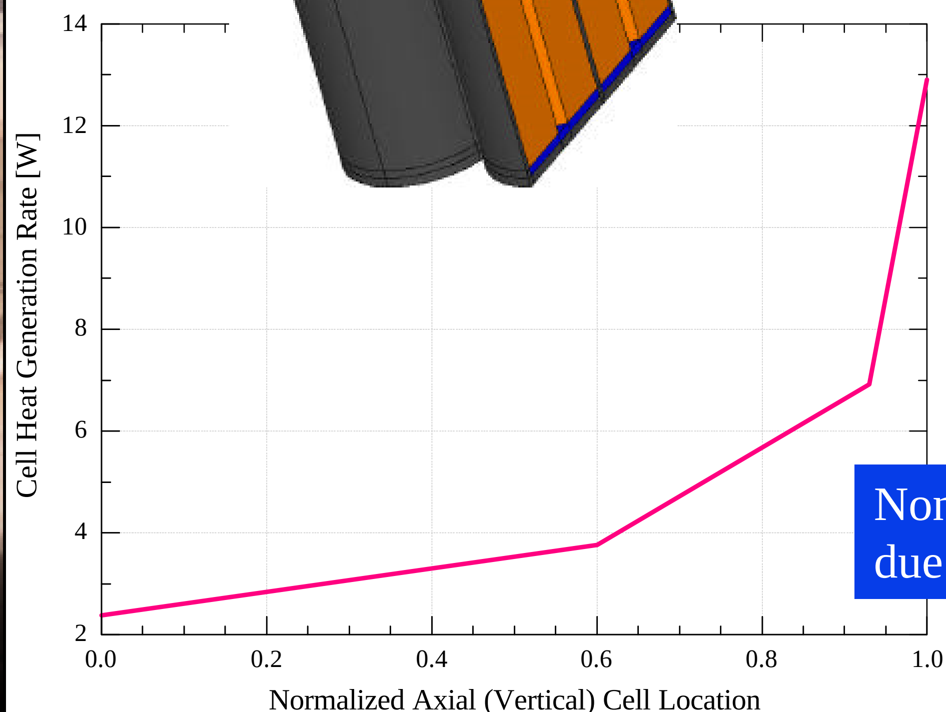
3-D Thermal Evaluation of Optima Module

CAD Finite element
thermal analysis



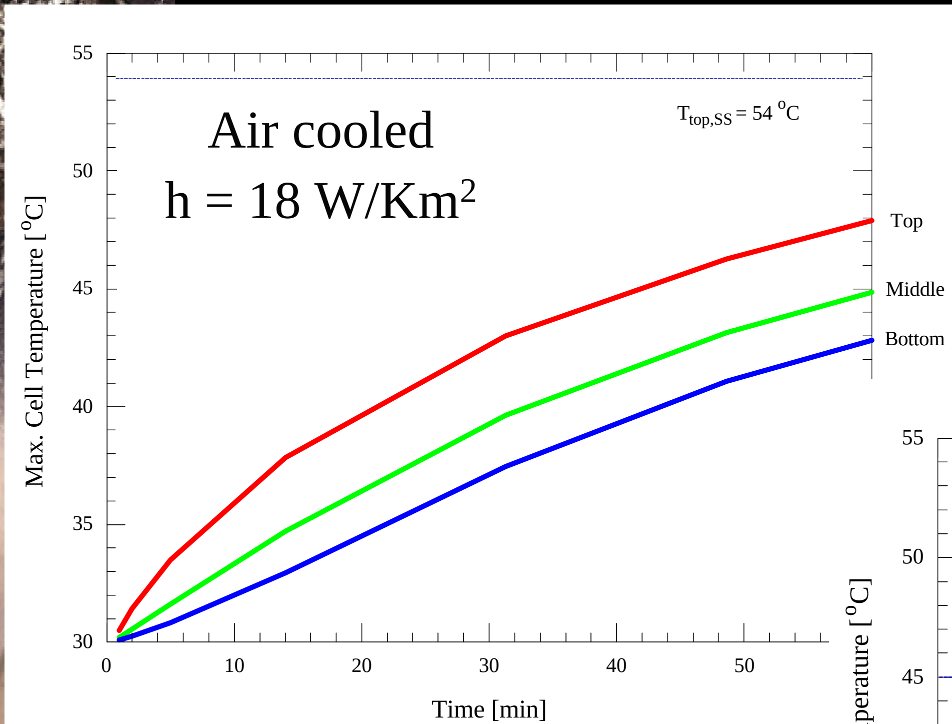




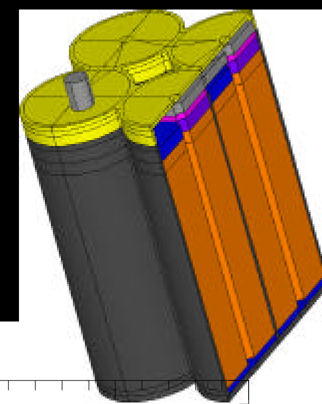


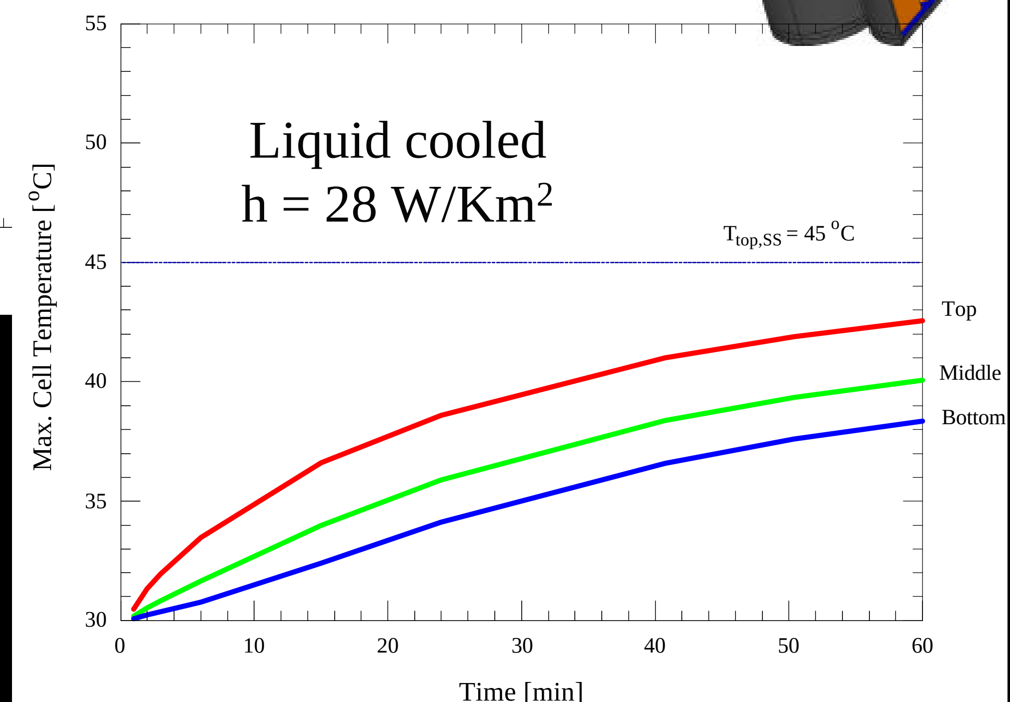
Non uniform heat generation
due to non uniform current density

Comparison of Air versus Liquid Cooling



Based on the same parasitic power

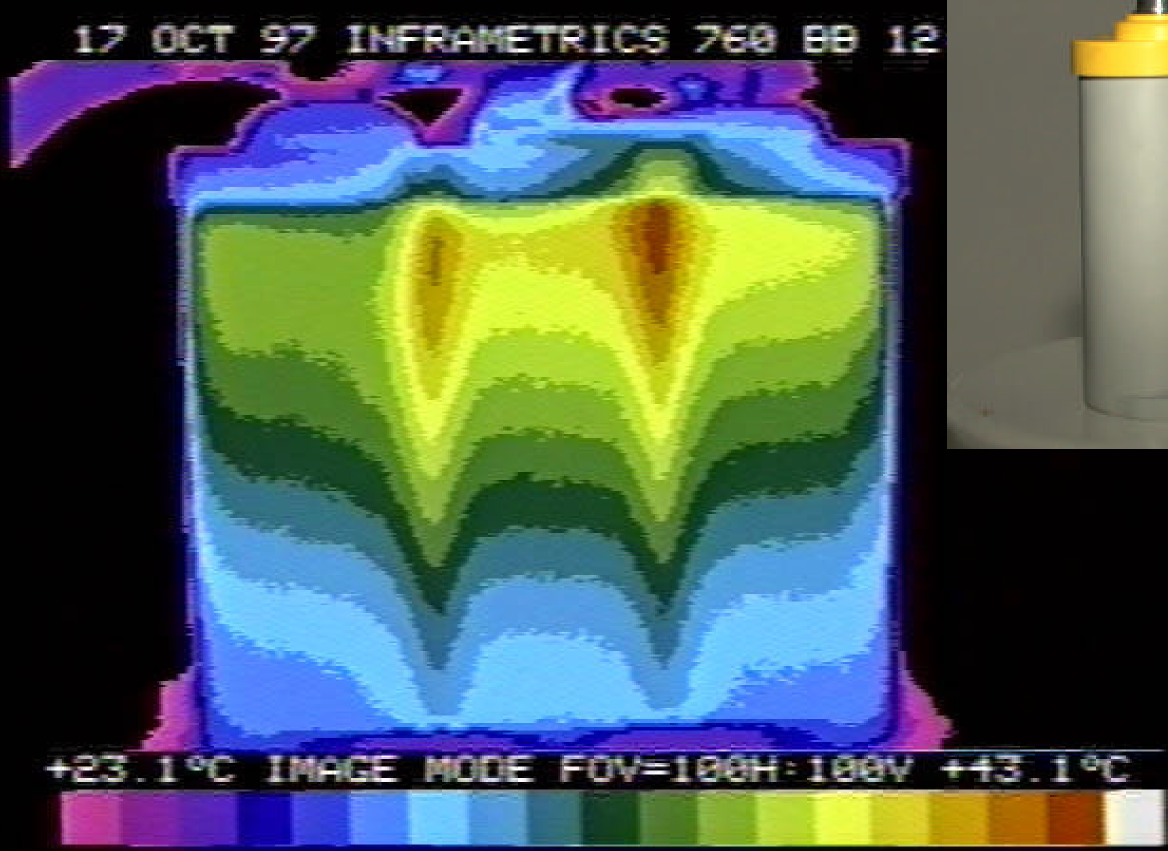




Liquid cooling more effective

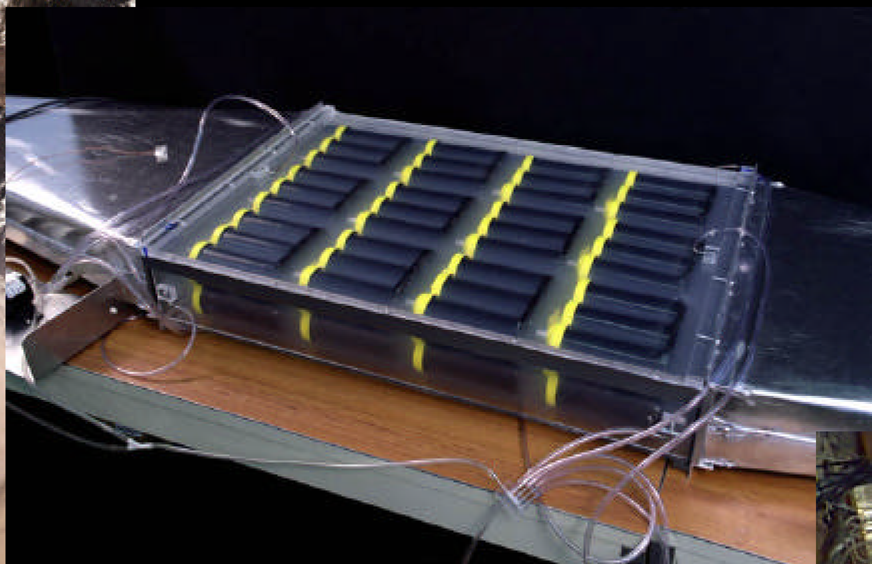
Infrared Thermal Imaging as a Diagnostic Tool

Image of Optima module during and HEV FUDS cycle

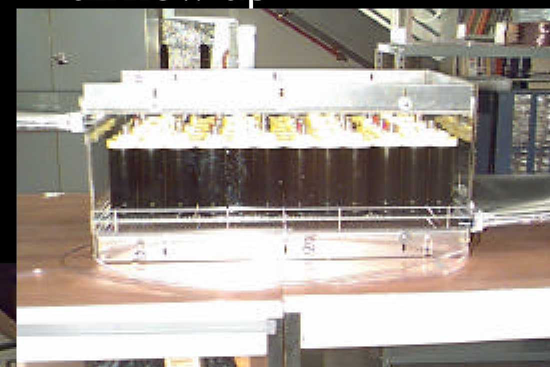


Evaluation of Two Optima Battery Packs for a Parallel HEV

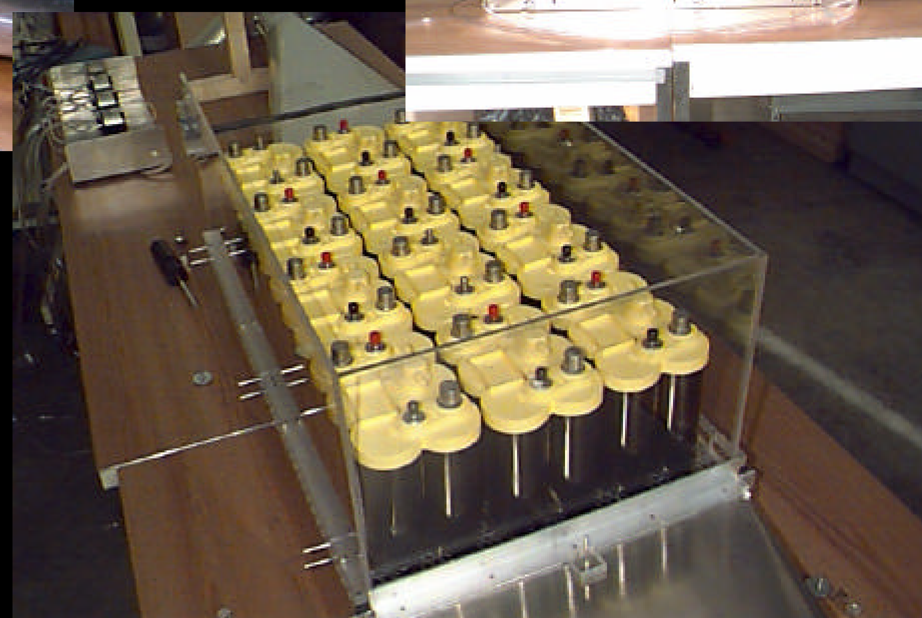
- Each pack consists of 12 Optima HEV modules in a 3X4 layout



Parallel flow:
modules upright
airflow up

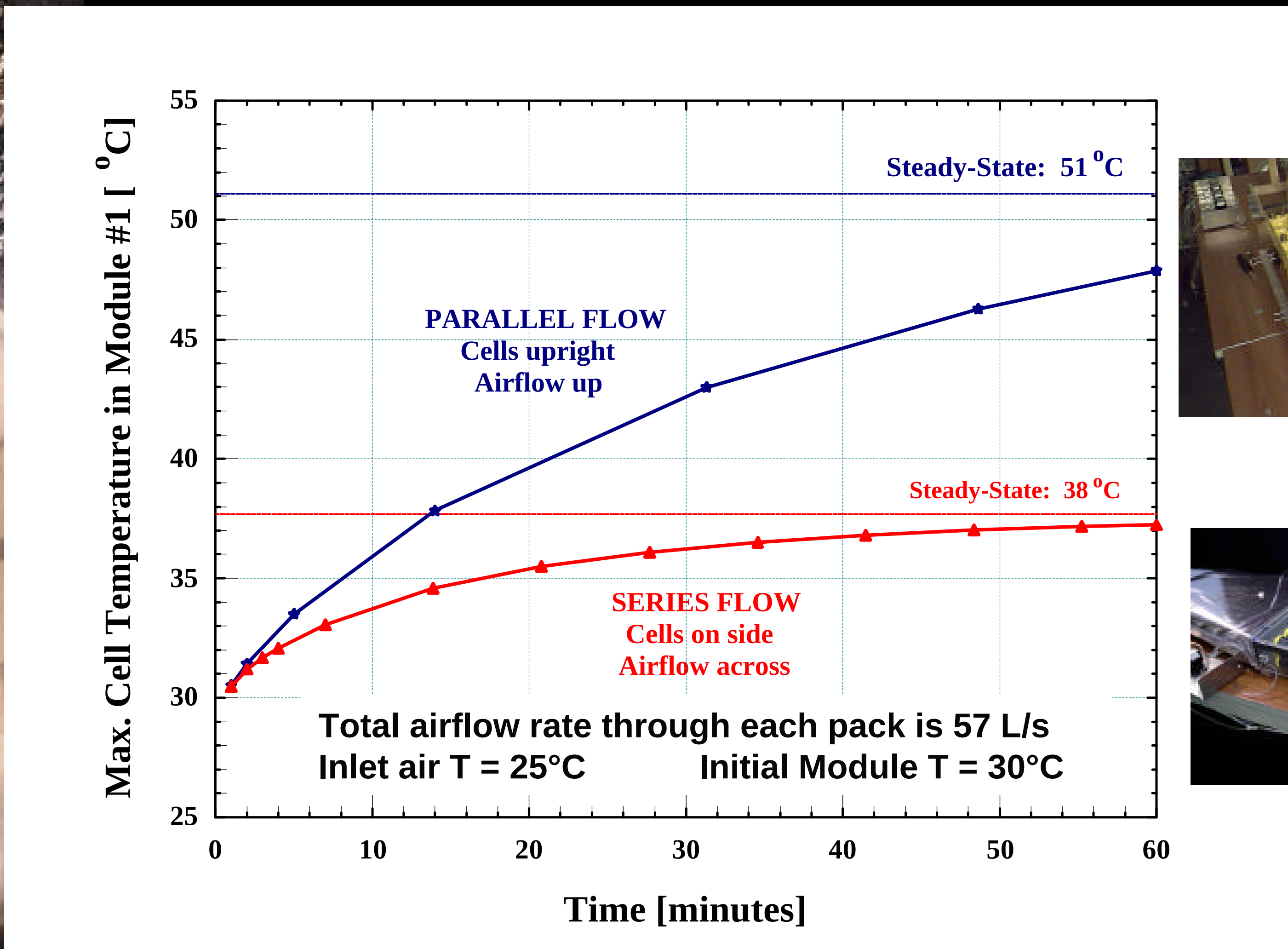


Series flow:
modules on side
airflow across



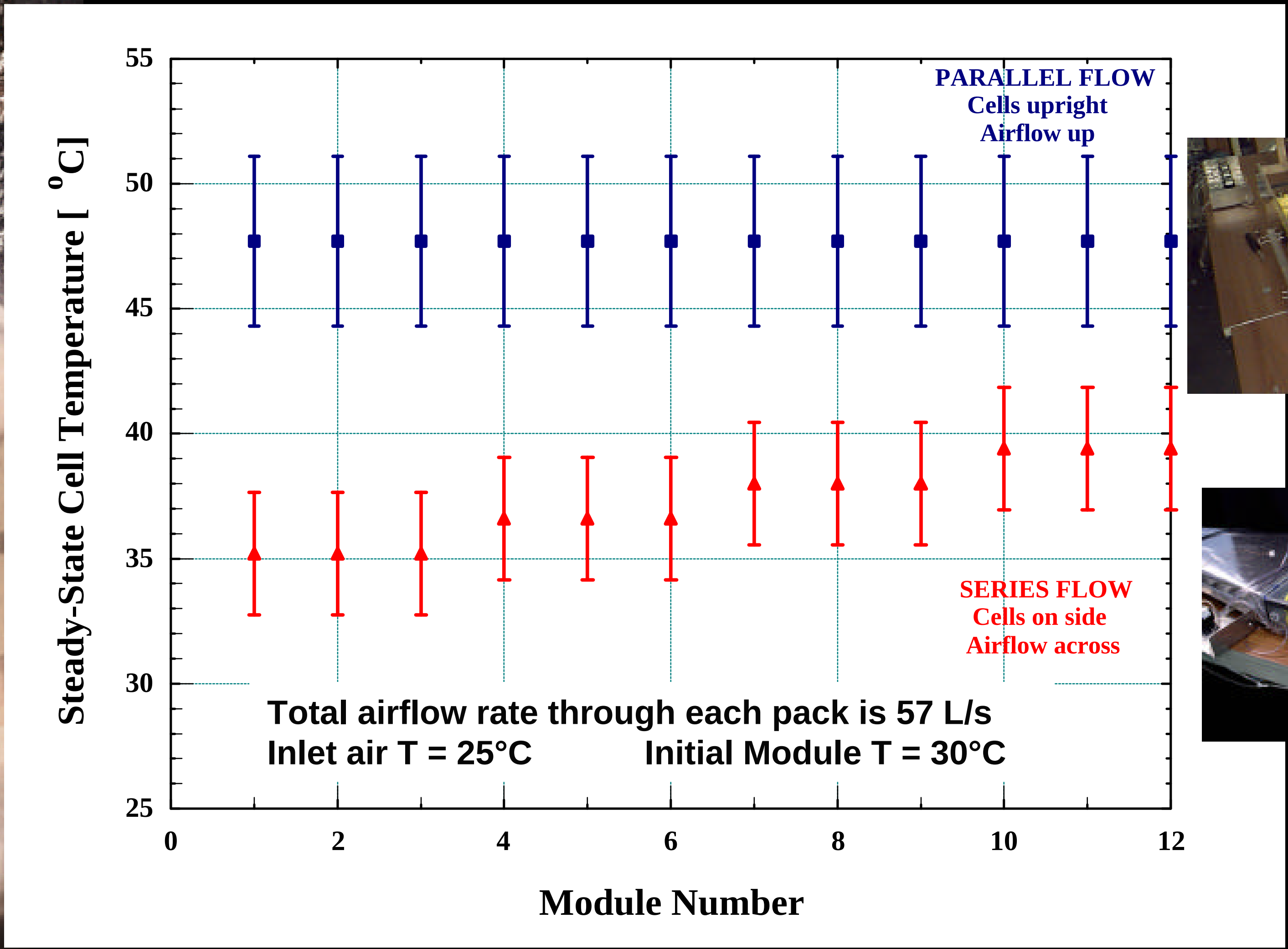
Transient and Steady-State Thermal Analysis of the First Module in two Packs

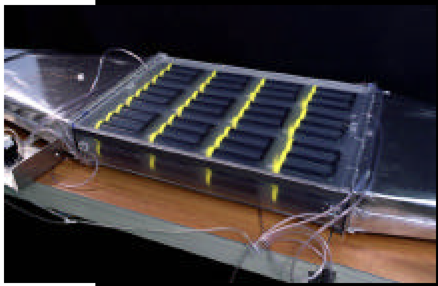
Higher flow rate and h results in lower temperature in series flow pack.



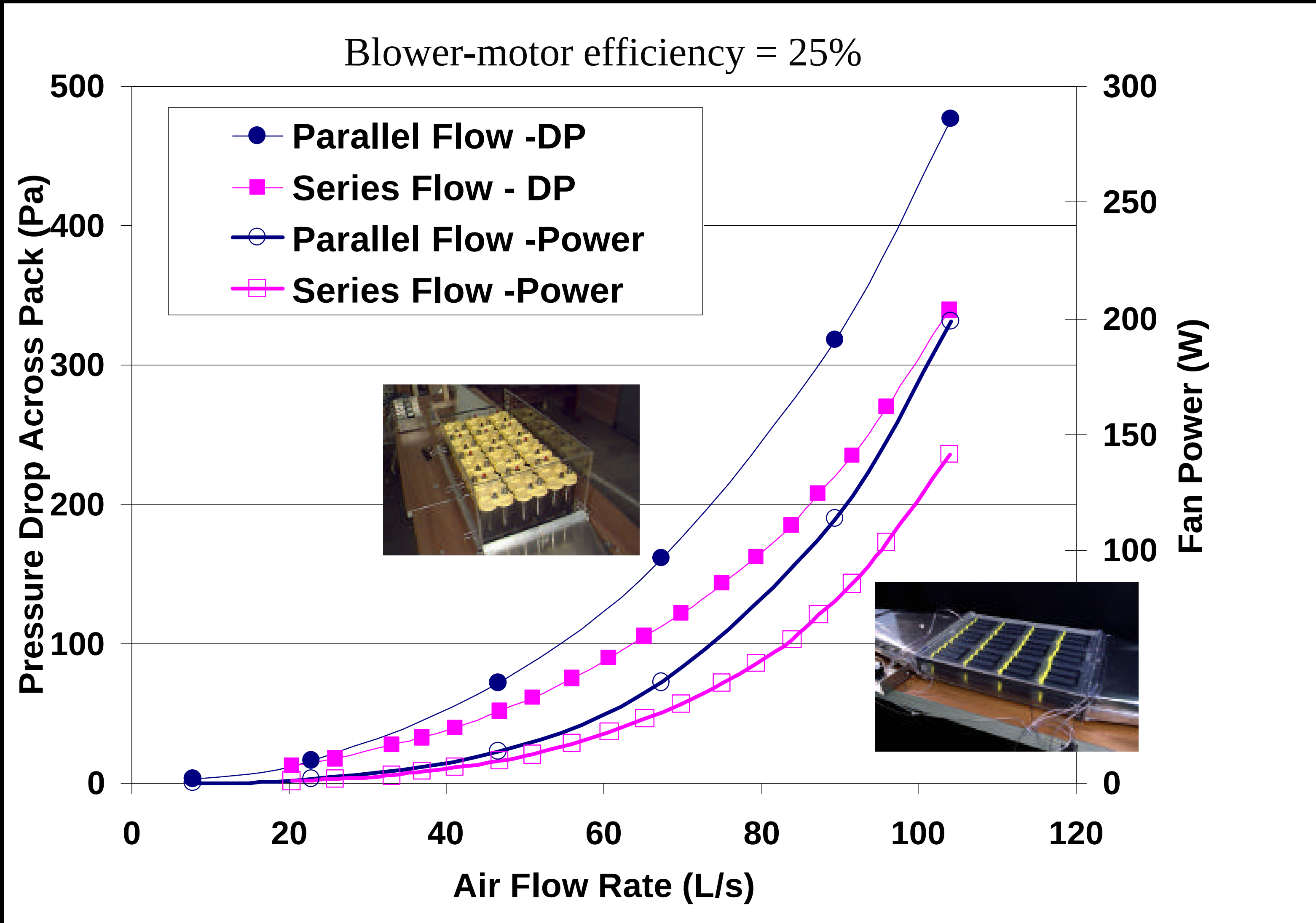
Steady-State Temperature Distribution in all Modules in the two Packs

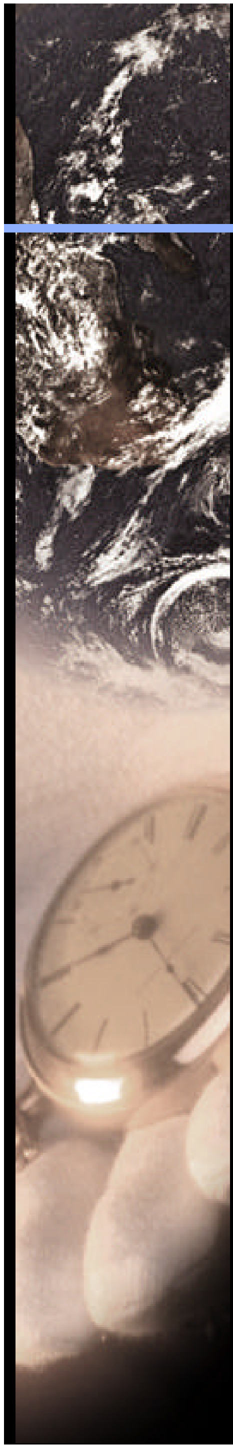
More uniform module temperature in parallel flow pack because of even flow distribution.





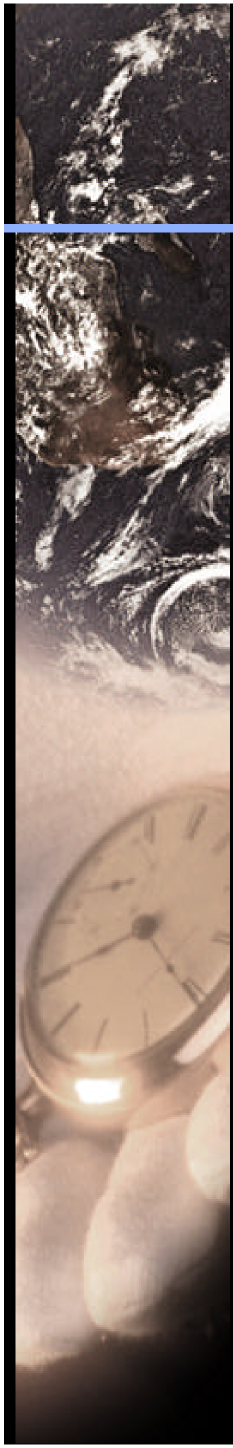
Experimental Pressure Drop and associated Fan Power for the two Packs





Concluding Remarks

- A well-designed thermal management system can improve performance and life cycle of EV/HEV battery packs.
- A step-by-step approach for designing and evaluating thermal management system was outlined.
  - Define requirements
  - Characterize thermal properties
  - Perform analysis - preliminary & detailed
  - Build, test, refine



Concluding Remarks

- Air thermal management system is less complicated than a liquid system, but less effective.
- For parallel HEVs, an air thermal management system is adequate, where as for EVs and series HEVs, liquid based systems may be required.
- For further information visit our Battery Thermal Management Web Site www.ctts.nrel.gov/BTM.