Cooling and Preheating of Batteries in Hybrid Electric Vehicles

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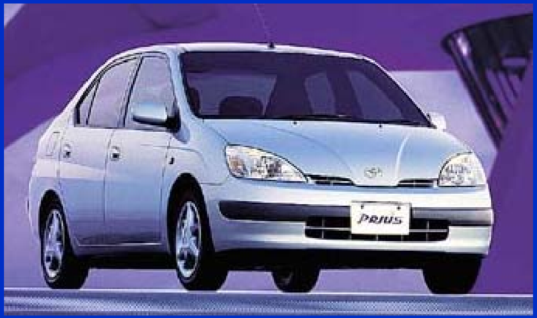
Outline

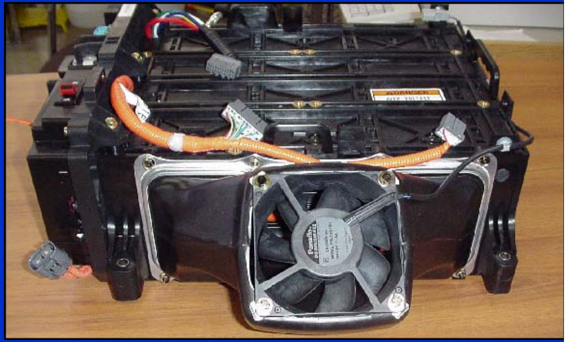
- Background
- Battery Thermal Management
- Cooling
- Preheating
  - Finite Element Analysis
  - Experiments
- Concluding Remarks

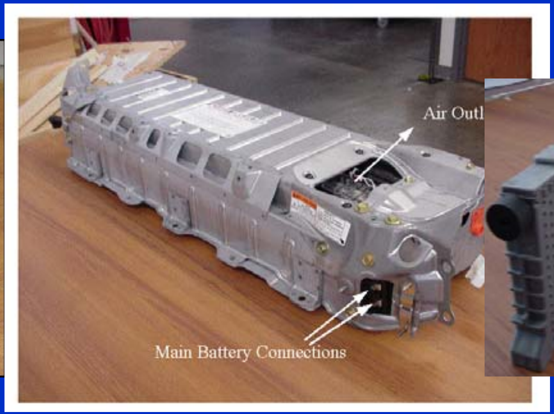
Background

- Hybrid electric vehicles (HEV) entering the market
  - Engine
  - Battery-powered motor

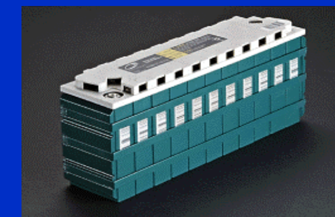


- HEV success depends on battery performance, life, and cost



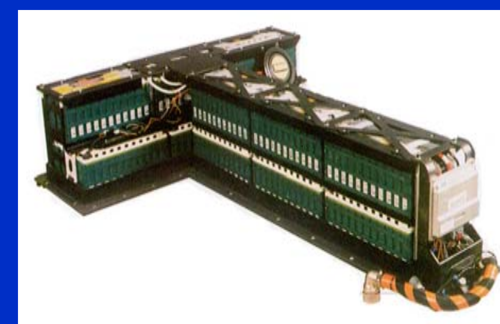


Battery Temperature is Important

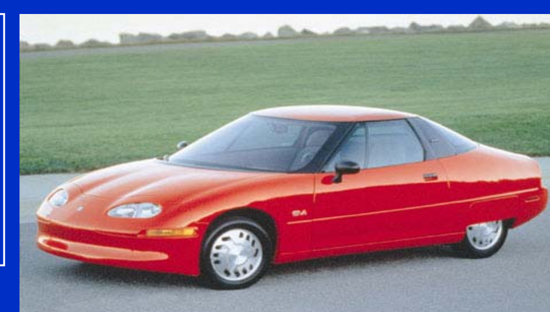


Temperature affects battery:

- Operation of the electrochemical system
- Round trip efficiency
- Charge acceptance
- Power and energy availability
- Safety and reliability
- Life and life cycle cost



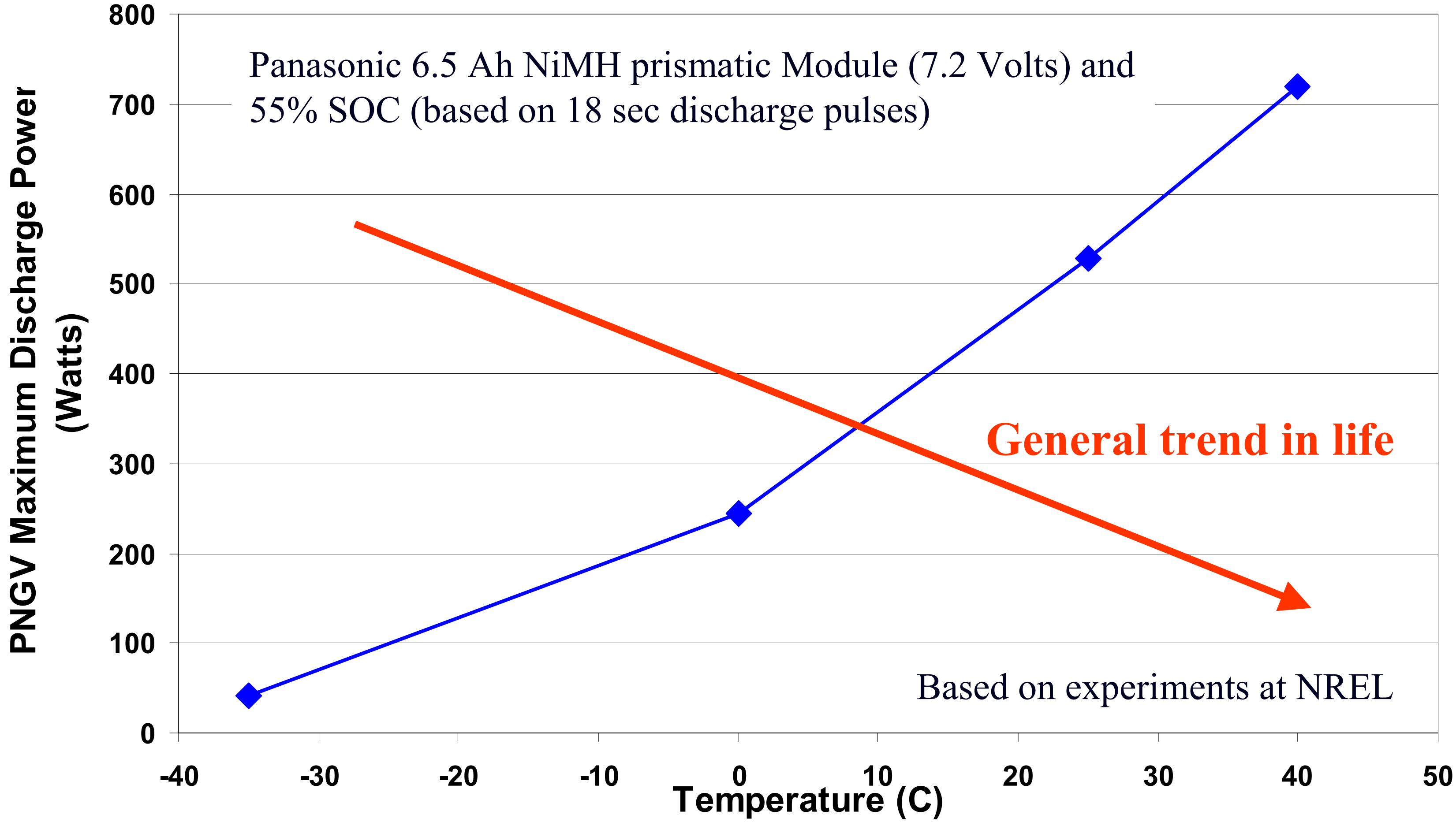
Battery temperature affects vehicle performance, reliability, safety, and life cycle cost



Background – cont.

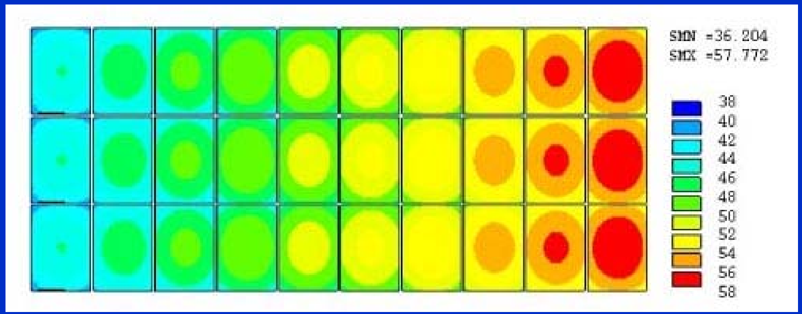
- Consumers expect satisfactory performance from hybrid vehicles at all climates
- Generally, as battery temperature increases
  - Power and energy capability of battery increase
  - Calendar and cycle life decrease
- At very cold temperatures batteries could not deliver the needed power and energy.

Impact of Temperature on Battery Discharge Power



Why Battery Thermal Management?

- Regulate battery to operate in the desired temperature range for optimum performance and life
- Reduce uneven temperature distribution in a pack batteries to avoid unbalanced modules/pack and thus, avoid reduced performance

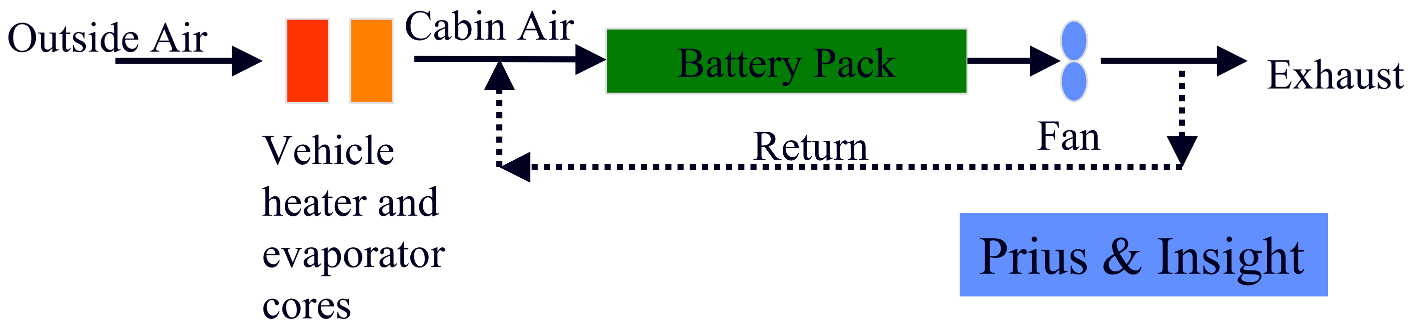


- **<u>Cooling</u>** in hot climates, mostly for avoiding premature degradation and improving safety.
  - Battery internal heating is dominant due to resistive heating
- **<u>Preheating</u>** in very cold climates, to overcome poor performance

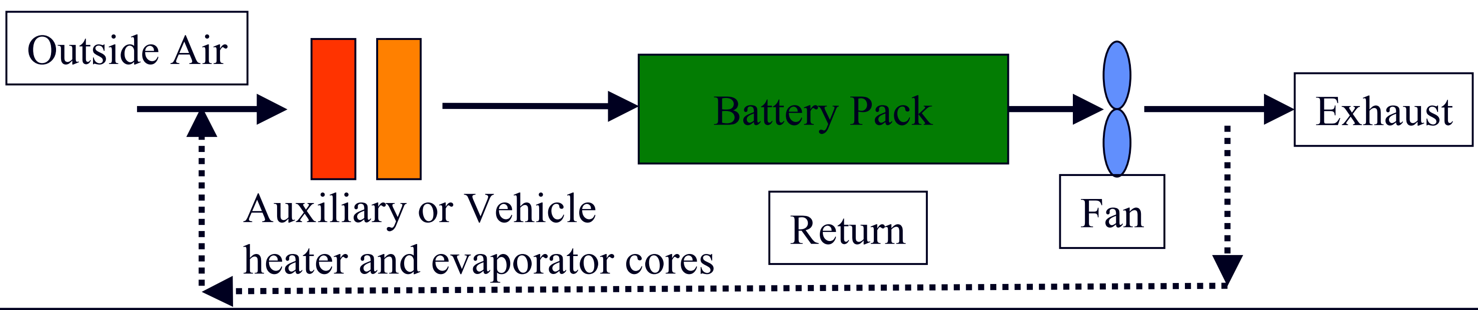
Cooling using Air Ventilation

Passive cooling- Outside Air Ventilation

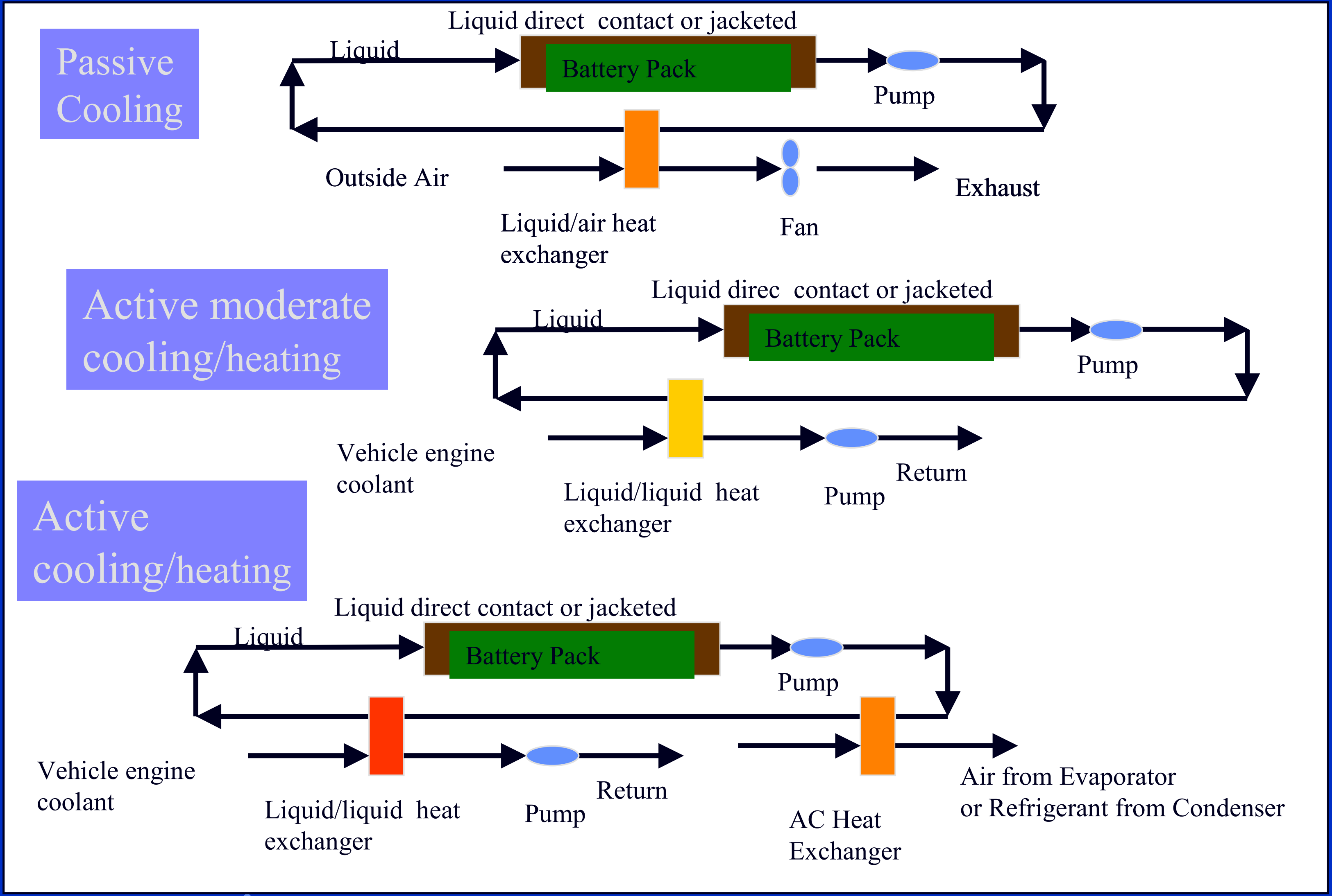
Passive cooling/heating- Cabin Air Ventilation



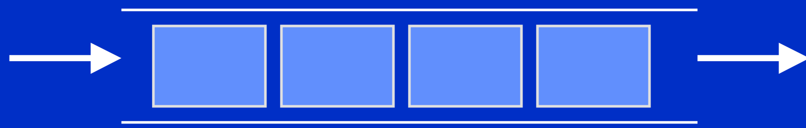
Active cooling/heating- Outside or Cabin Air

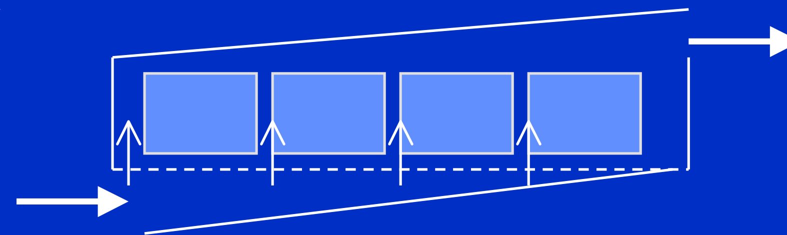


Cooling using Liquid Circulation



Series vs. Parallel Air Distribution

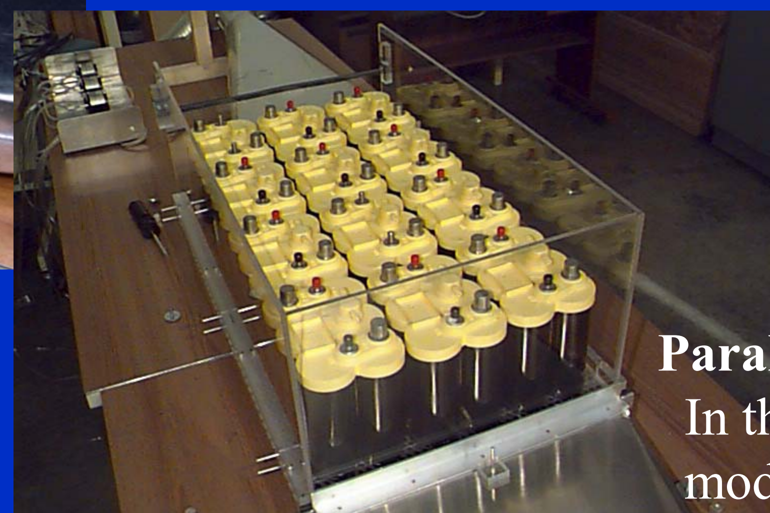




Balancing pressure drops with proper manifold

Series flow

In this case, modules on side airflow across



Parallel flow

In this case modules upright airflow up

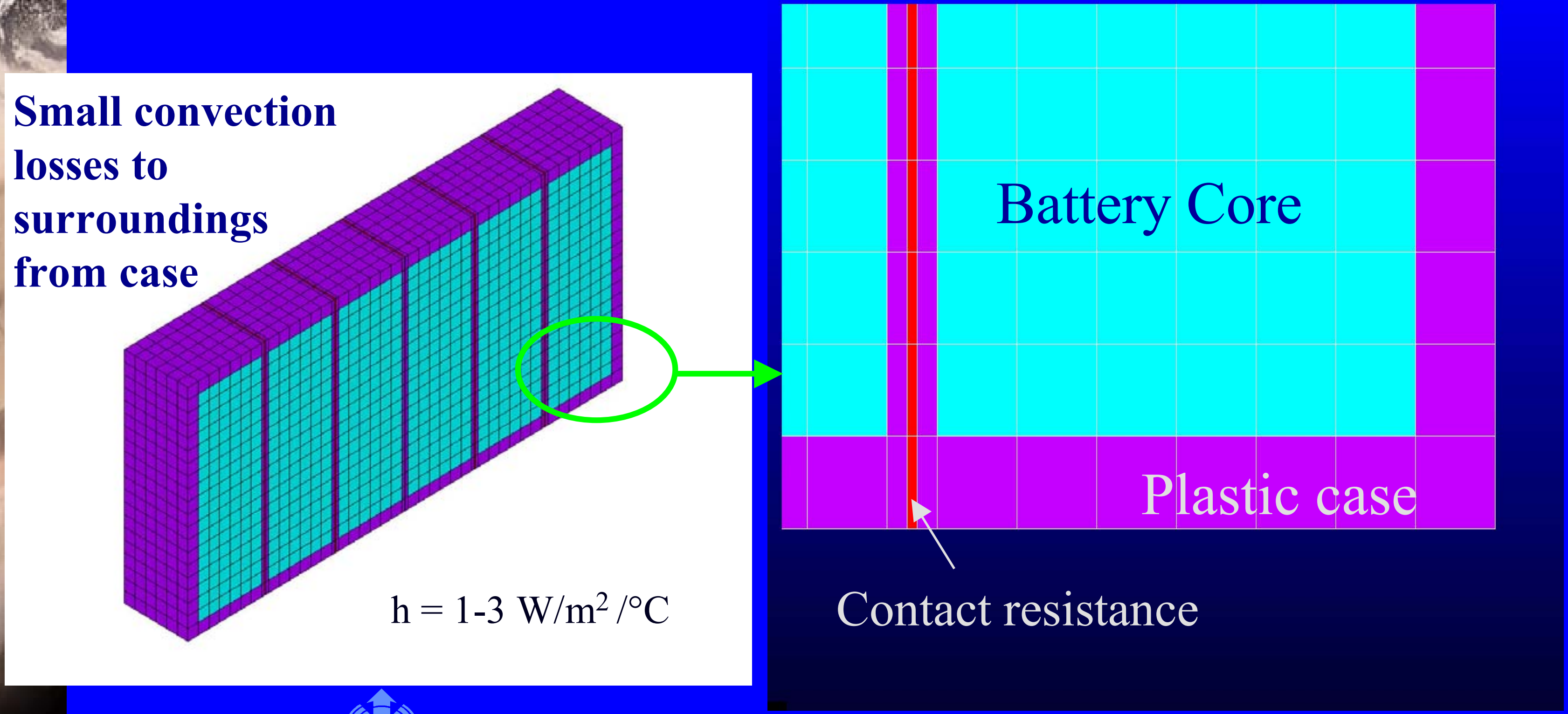
Preheating Study

- Sources of energy for on-board preheating
  - Heat from engine
  - Electricity from battery
  - Electricity from generator/inverter
- Identify the most effective preheating technique
  - External heating techniques:
    - Electrically heated thermal jackets
    - A sealed enclosure with an internal heating element
    - Circulating a fluid heated from the engine
  - Internal heating techniques:
    - Resistive heating elements embedded within the batteries
    - Apply current to the battery terminal
- Perform FEA thermal analysis for a rectangular module
- Perform feasibility tests.

Case 1

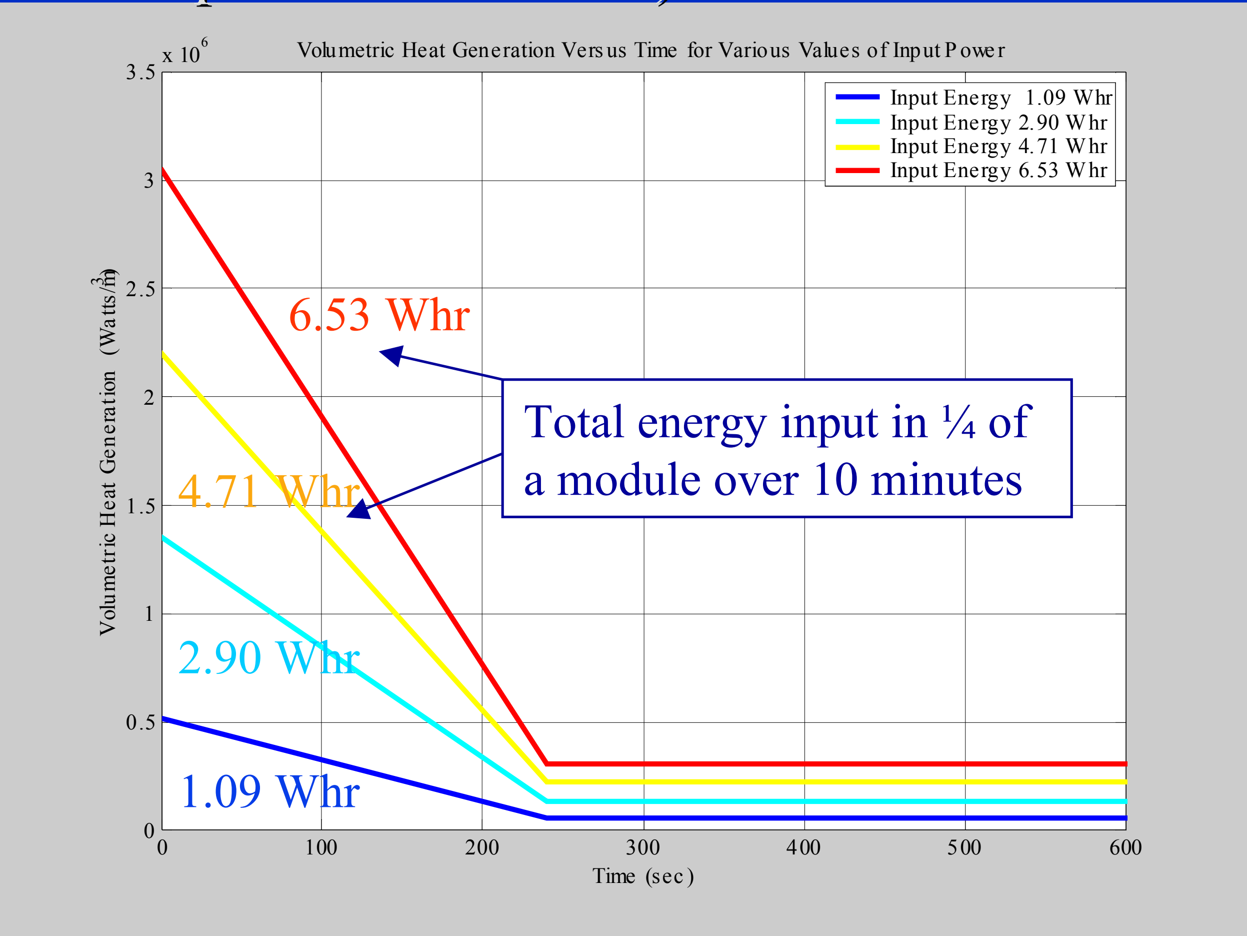
Internal Core Heating using Battery Resistance

- Geometry: rectangular modules consisting of six cells
- Heat transfer by conduction from core to exterior
- Half FEA model



Transient Volumetric Heat Generation Applied

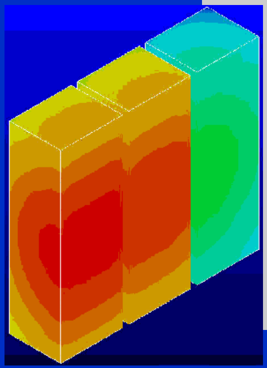
- Heat generated in the core from battery resistive heating (decreases as temperature increases)

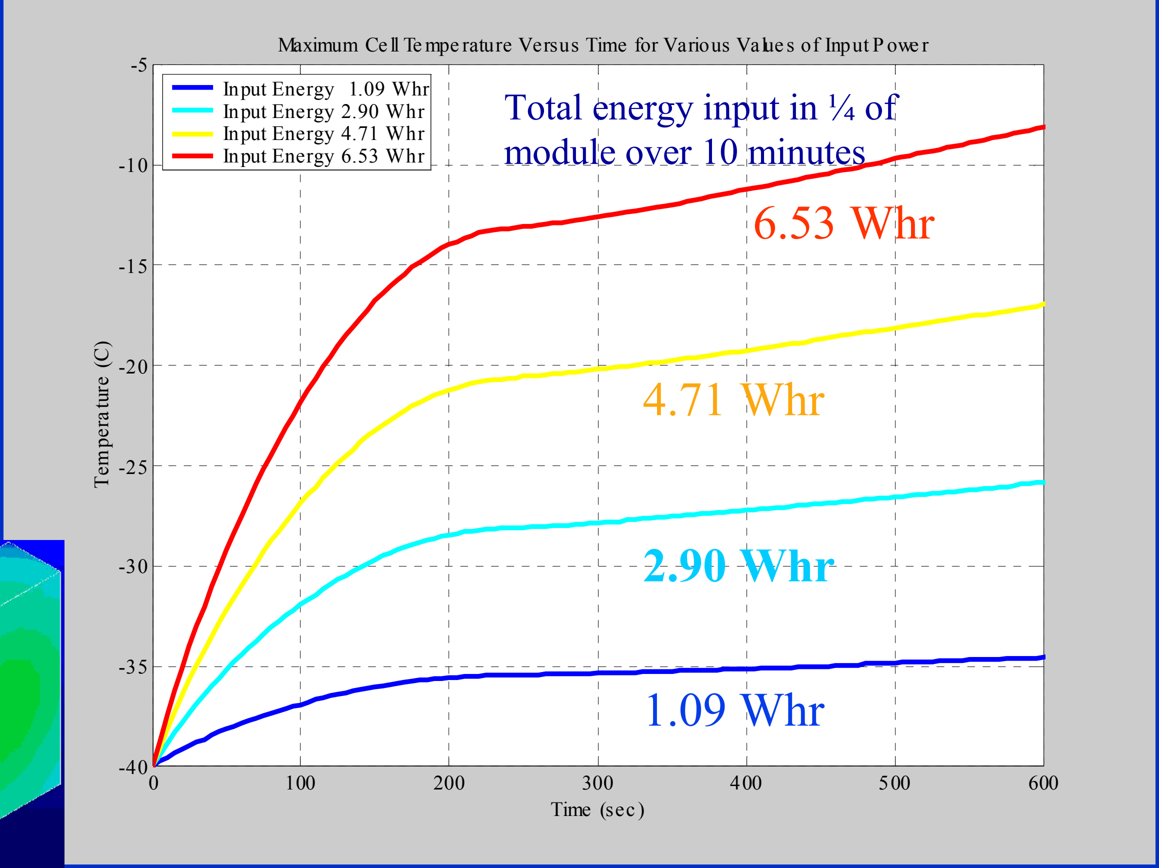


Maximum Temperature versus time for Internal Core Heating

- Temperature increases with time and amount of internal heating energy

- After 2 minutes the slope of temperature rise decreases because heating rate decreases.

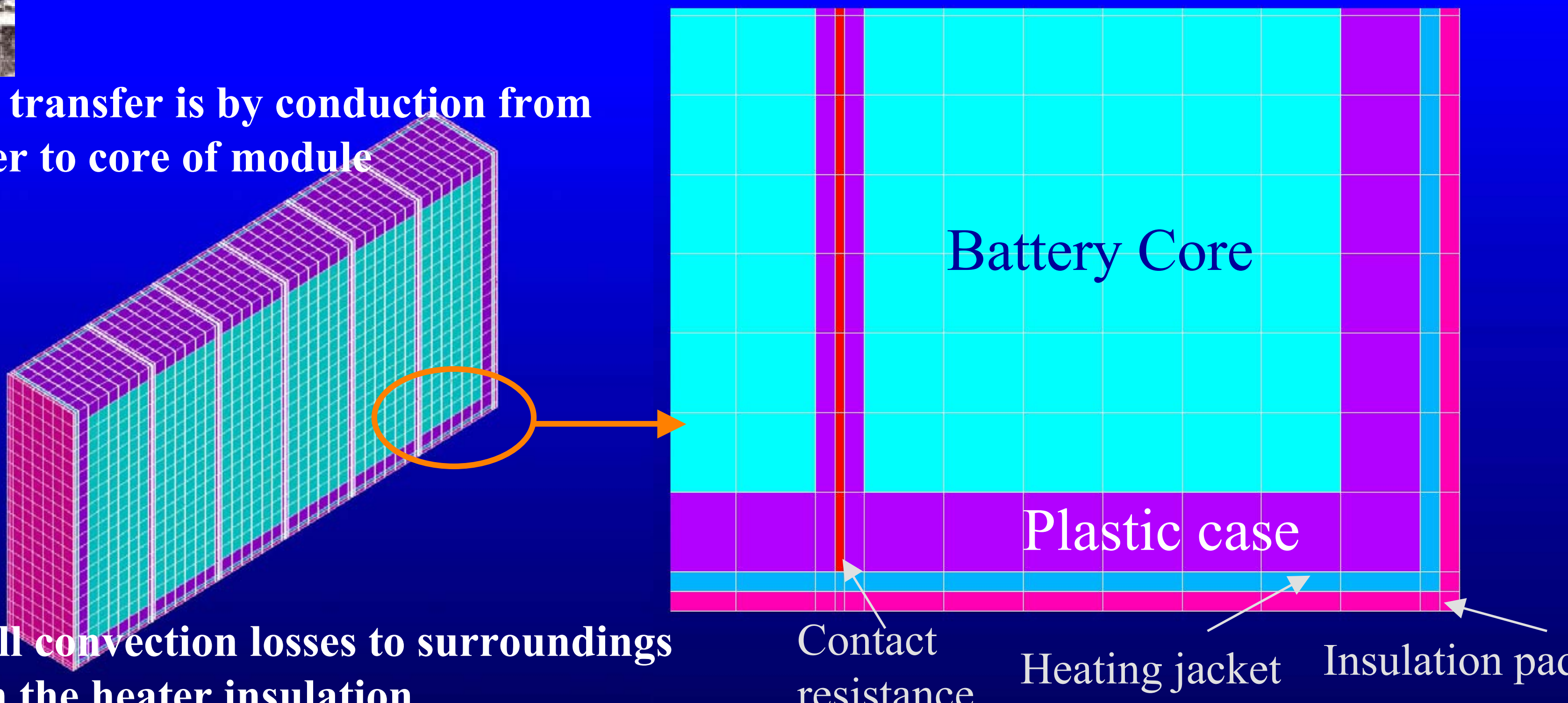




External Electric Jacket Heating around Module

- Geometry: rectangular modules consisting of six cells
  - Jacket heater: 0.0625 inch thick with additional 0.0625 insulation
- Half FEA Model

Heat transfer is by conduction from heater to core of module

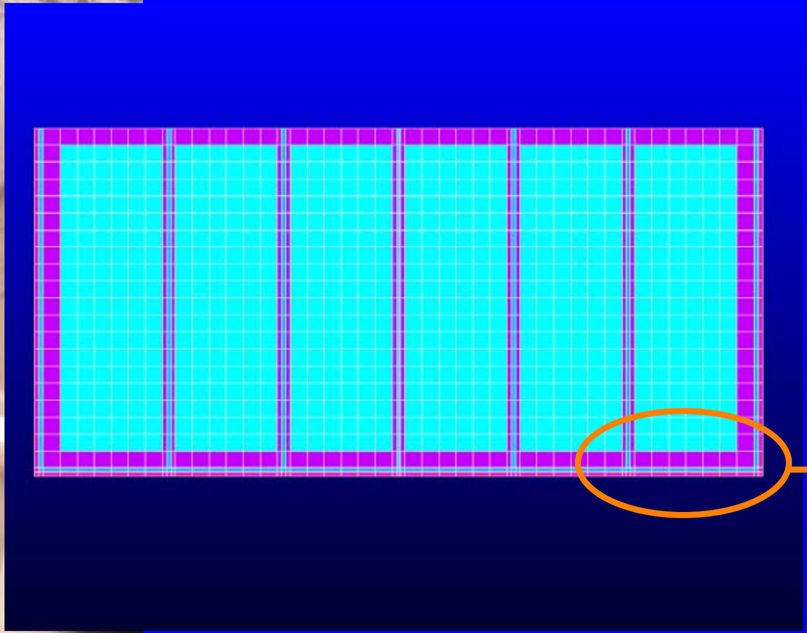


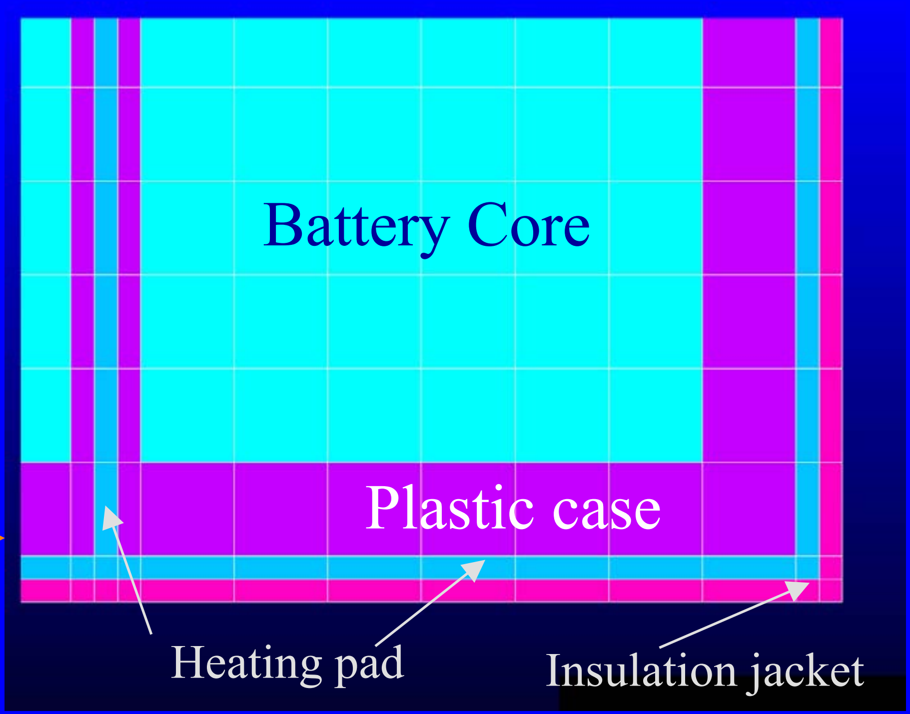
Small convection losses to surroundings from the heater insulation

Case 3

Internal Electric Jacket Heating around Cells

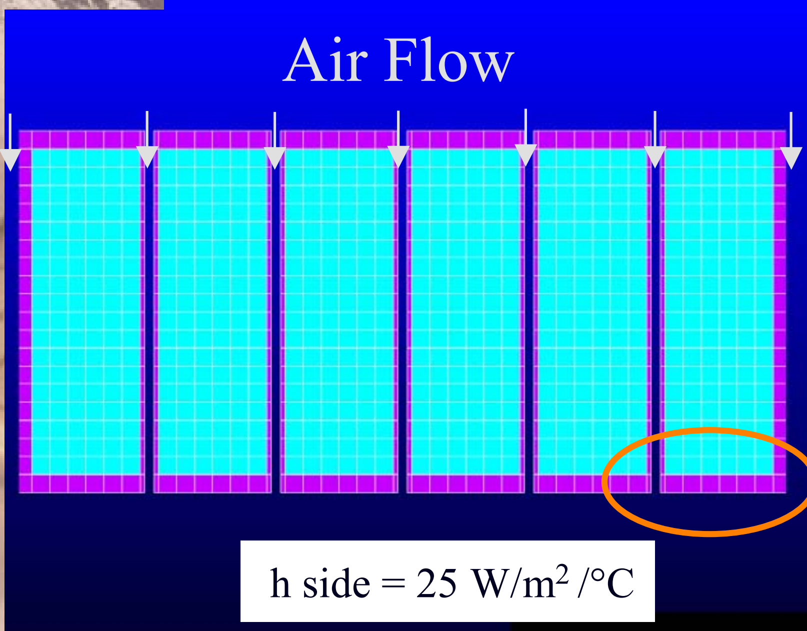
- Geometry: rectangular modules consisting of six cells
  - Jacket heater: 0.0625” thick with additional 0.0625” insulation

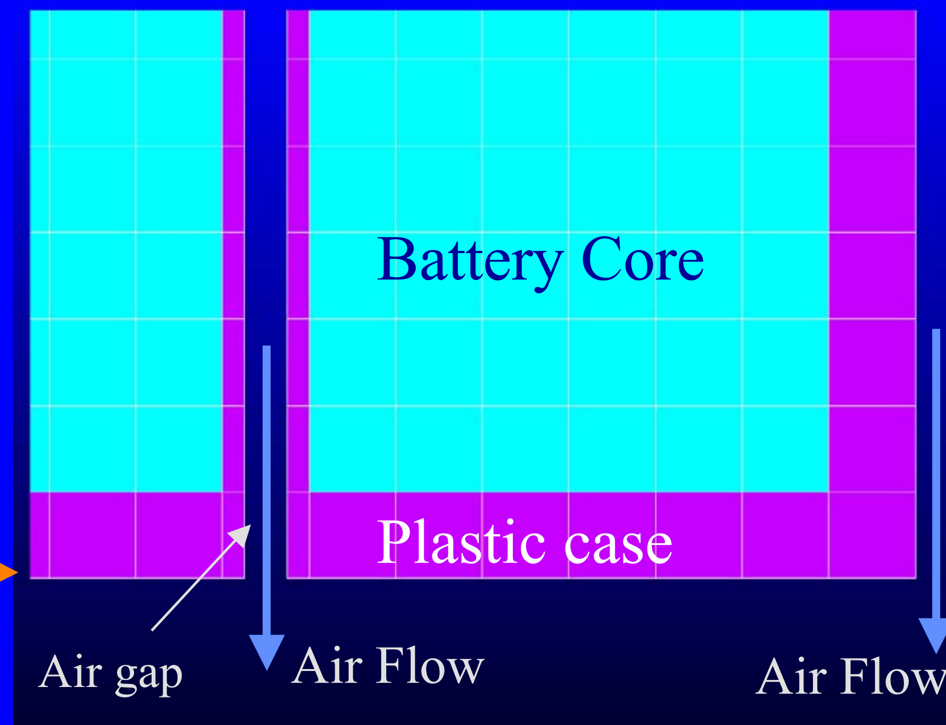




Internal Heating Using Fluid between each Cell

- Geometry: rectangular modules consisting of six cells
  - Air gap between each cell: 3.1 mm

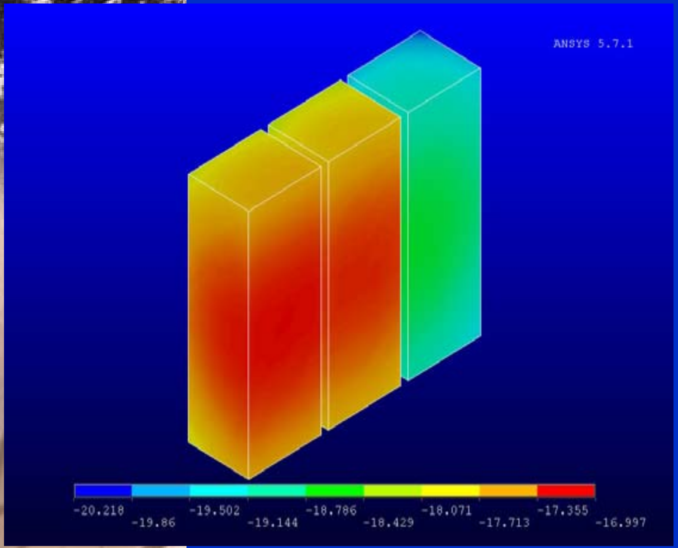




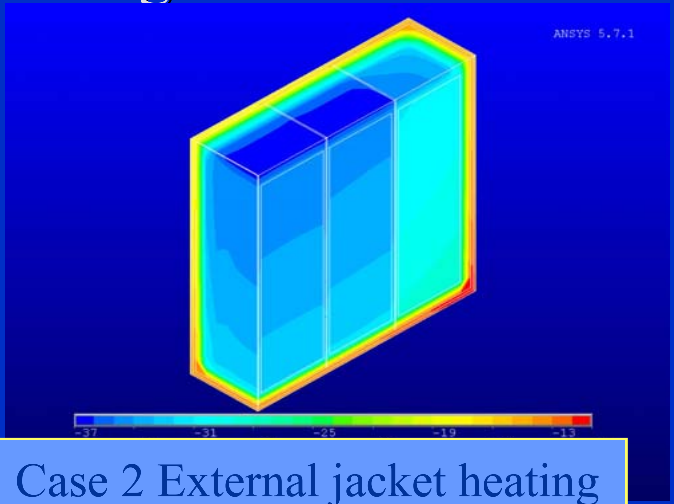
h horizontal= 2-5 W/m^2 /°C

Comparison of Four Heating Cases

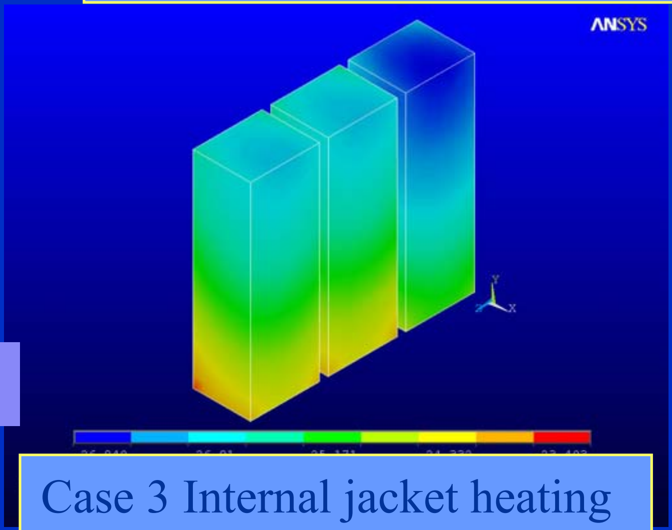
- The most uniform heating was with internal core heating (Case 1)



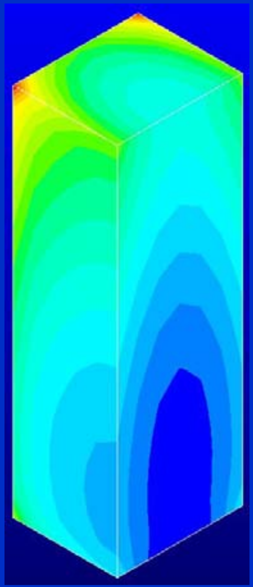
Case 1 Internal core heating



Case 2 External jacket heating



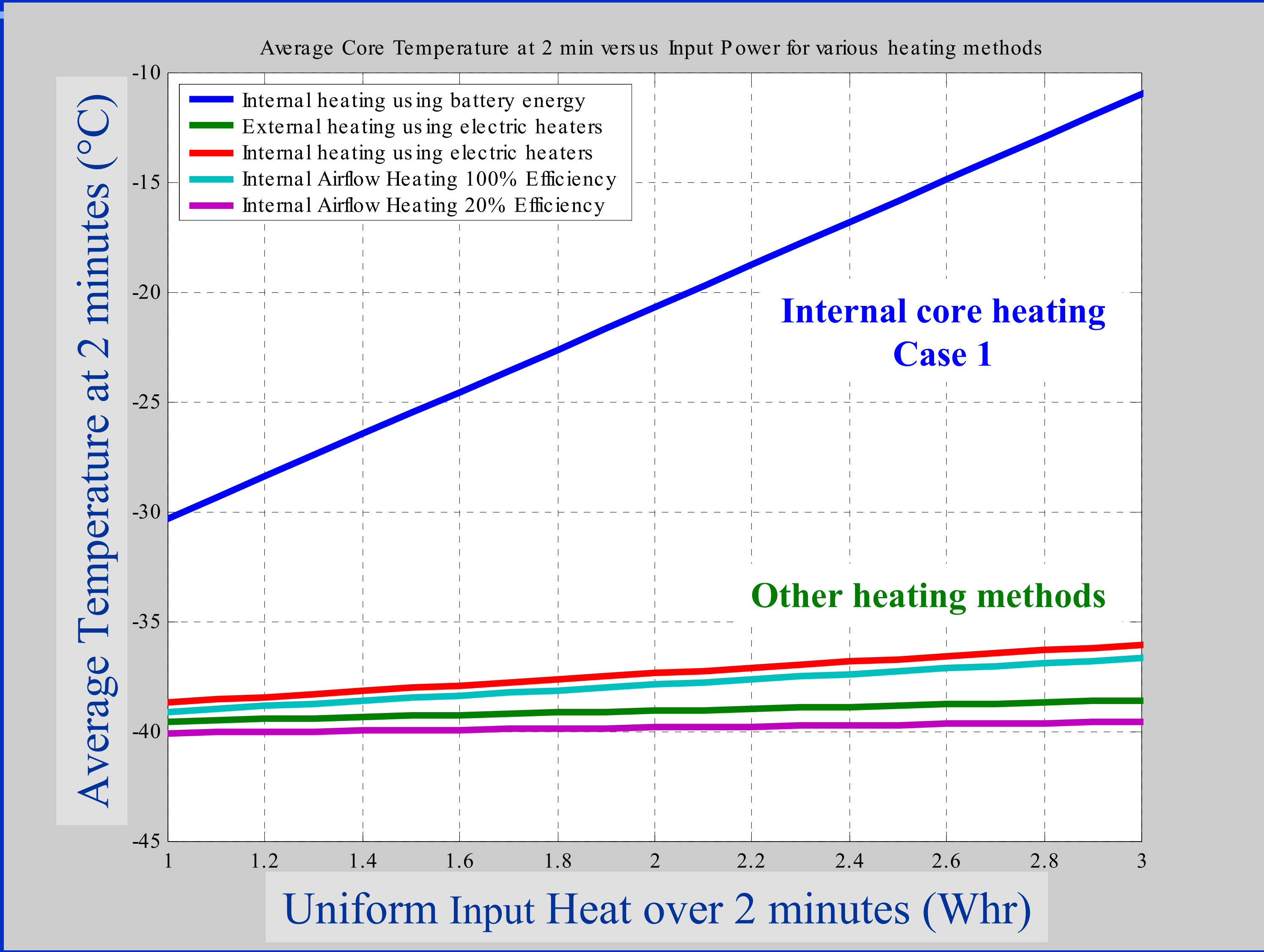
Case 3 Internal jacket heating



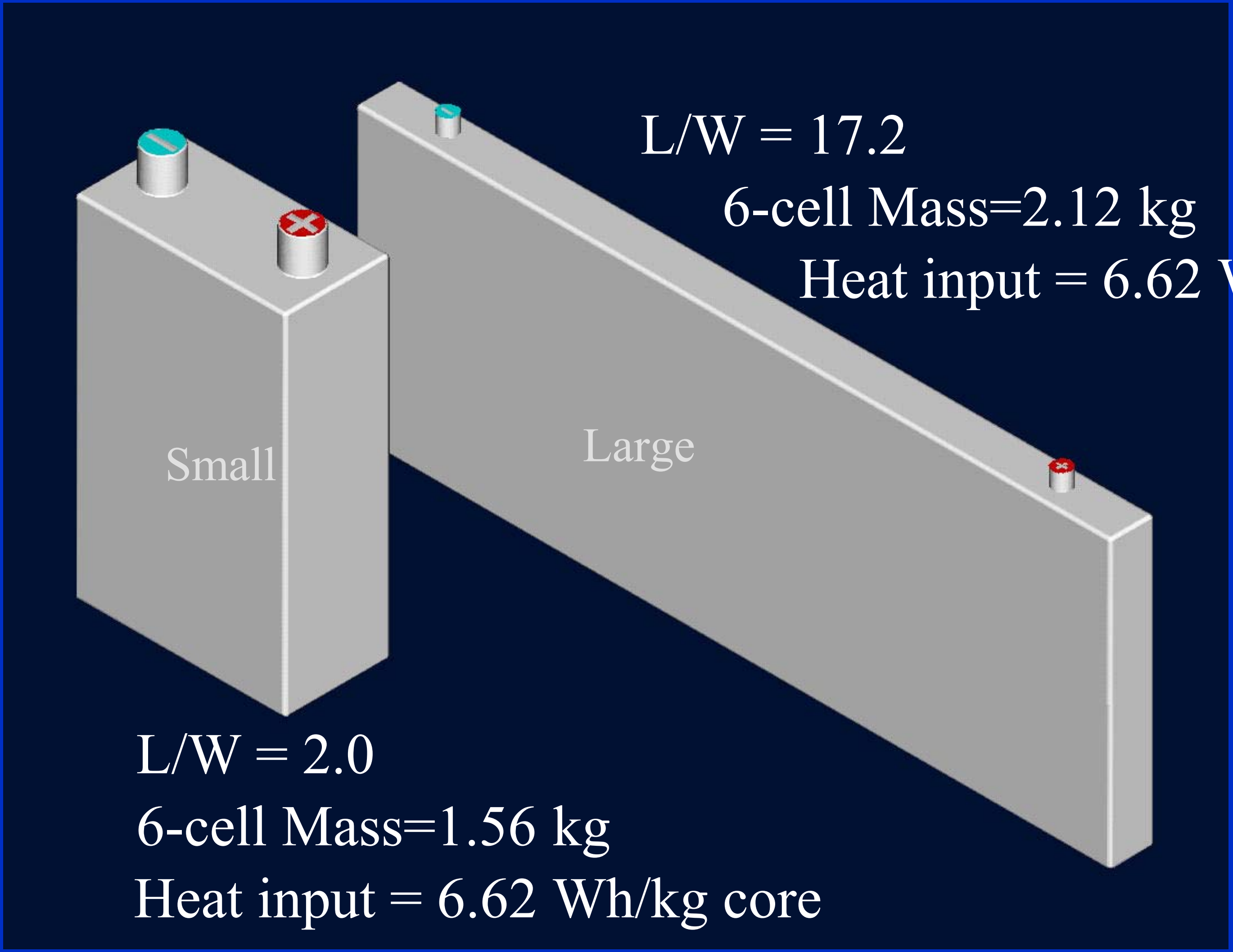
Case 4 Internal air heating

The same temperature scale

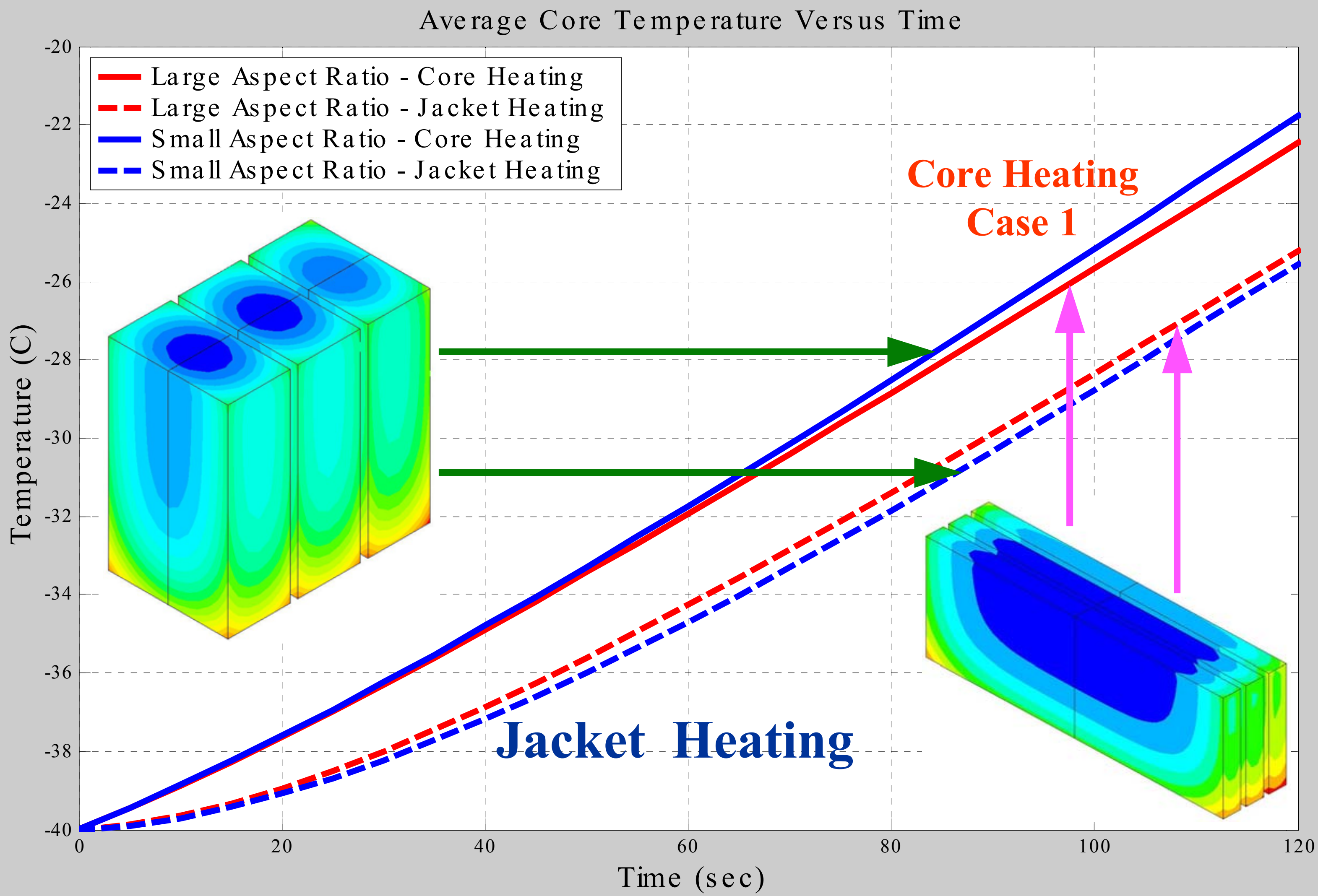
Average Core Temperature at 2 minutes for various Heating Methods



Effect of aspect ratio studied to see if it has any impact on heating effectiveness



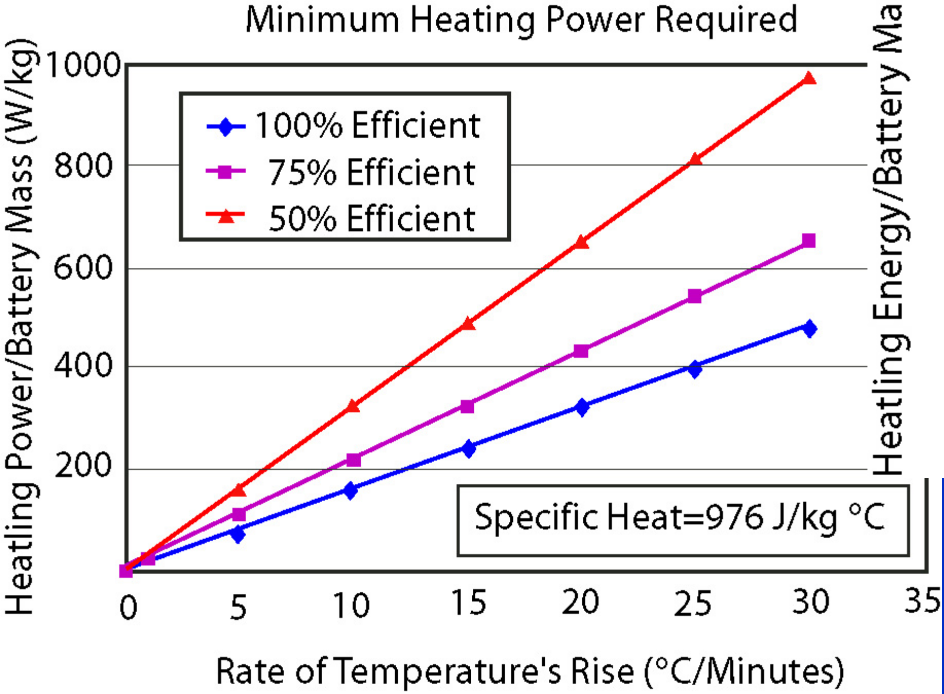
Comparison of Heating Effectiveness for the same Whr heat/kg

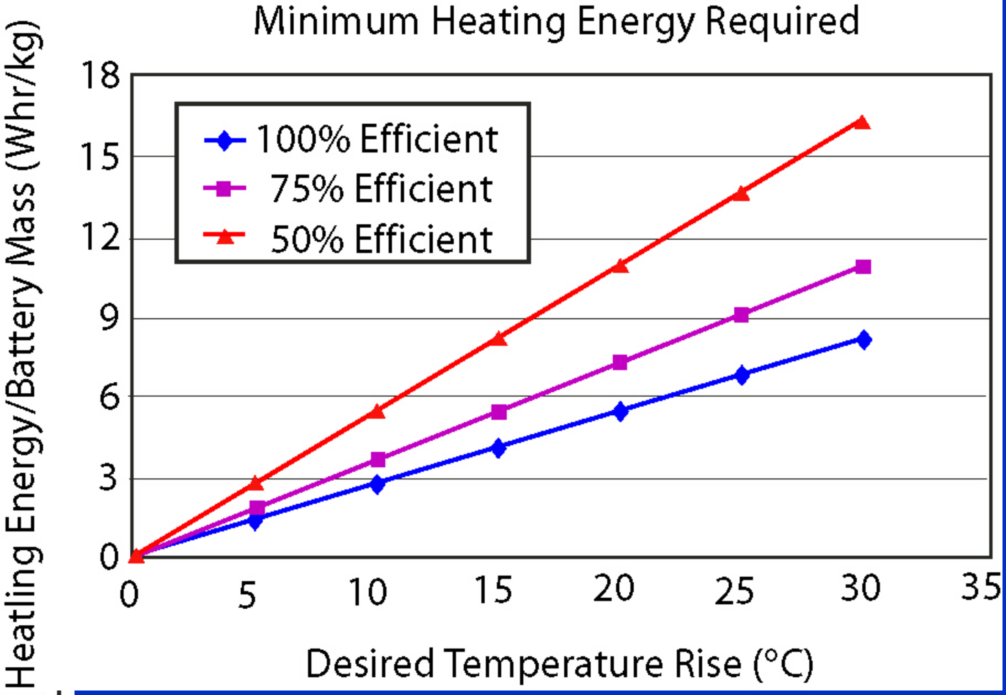


Thermal Analysis Observations

- Electric heating raises the battery temperature faster than heating with fluids.
- The most uniform temperature distribution was with internal core heating
- With the same heat input, average core temperature was raised faster with core heating.
- These observation not changed for batteries with different aspect ratios.

How much Energy and Power for Preheating a Battery?





To raise the temperature of a 40 kg battery pack from -30°C to 0°C in 2 min, 9.76 kW of power (or about 325 Wh of heat energy) is required for a 100% efficient process.

How to apply the more effective core heating method?

- At low temperatures battery resistance is high
- Charging/discharging heats the battery (I^2R)
- DC currents could damage batteries
- Applying high frequency alternating currents (AC) may heat up the battery without too much energy loss and battery damage
- Initial feasibility work done in collaboration with University of Toledo
  - 60 Hz AC heating on lead acid and NiMH batteries
  - High frequency (10-20 kHz) AC heating to a NiMH pack

Applying 60 Hz AC Power is Effective in Warming Batteries

- Measured pulse DC resistance (pulse power capability) of a lead acid module at very cold temperatures before and after applying 60 Hz AC heating

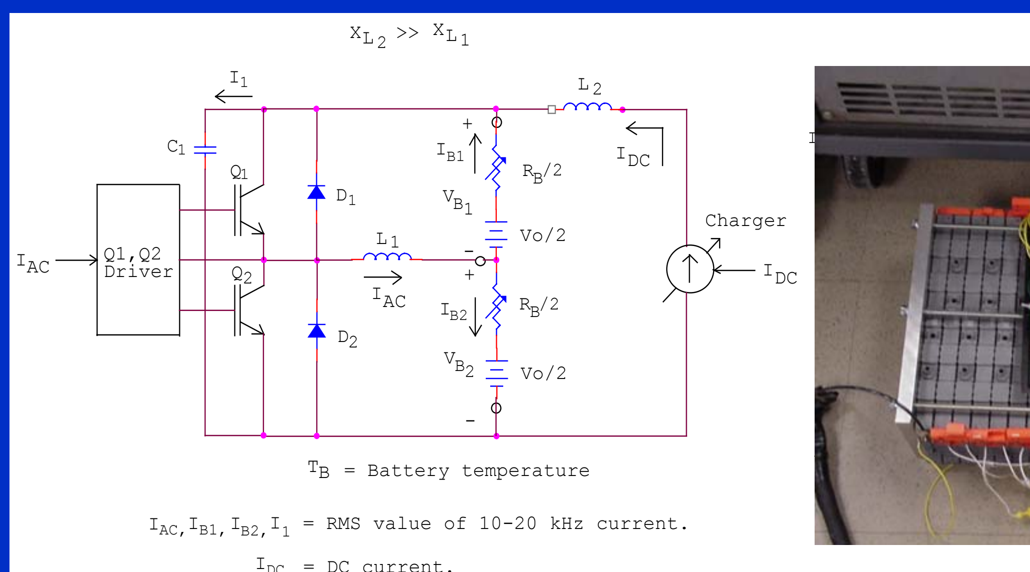
Initial Battery Temp = –40°C

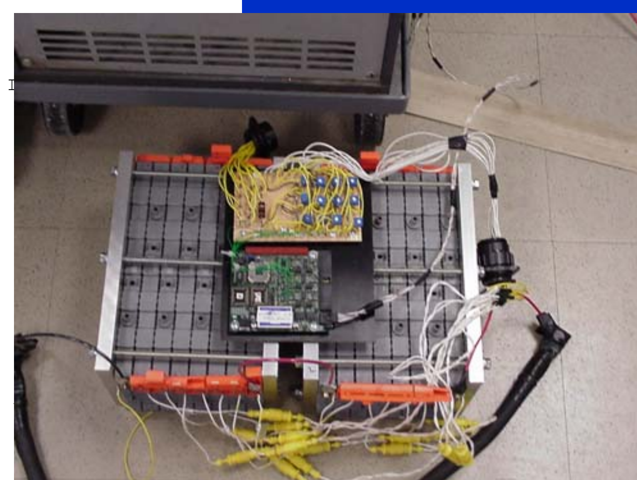
AC Heating	Internal R mil Ohm	Peak current (A)	Estimated T (°C)
None	108	100	-40
3 min	19.6	210	-4
6 min	14.7	250	+6
9 min	13.5	270	+9

- 60 Hz AC (off-board) more suitable for electric vehicles

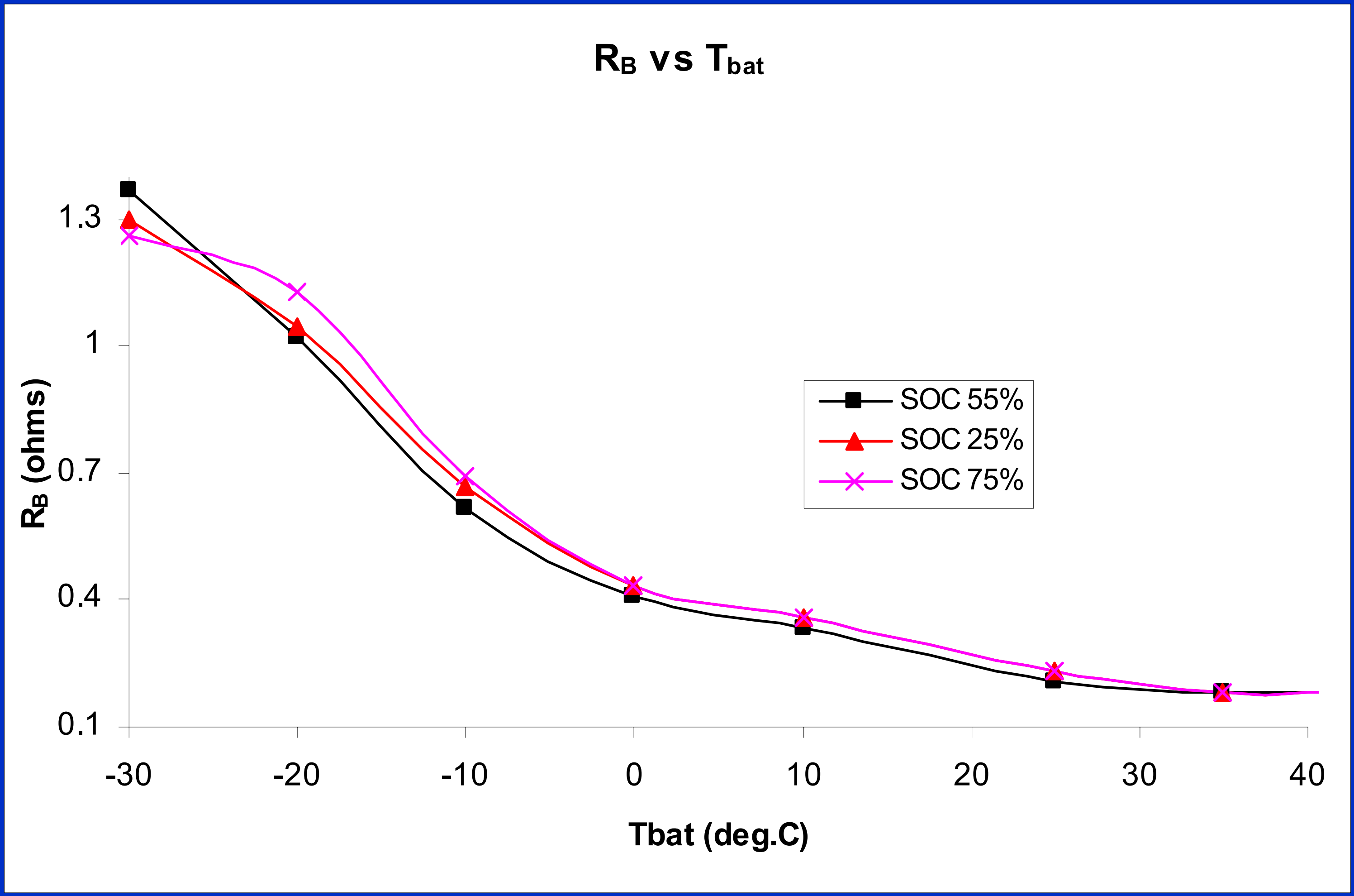
High Frequency AC Heating Evaluation

- Higher frequencies reduce size of power electronics for potential on-board hardware.
- Applied 10-20 kHz current to a Panasonic NiMH battery pack (16-module, 115.2 V, 6.5 Ah) using a special heater circuit.
- Measured resistance and peak power before and after applying high frequency current

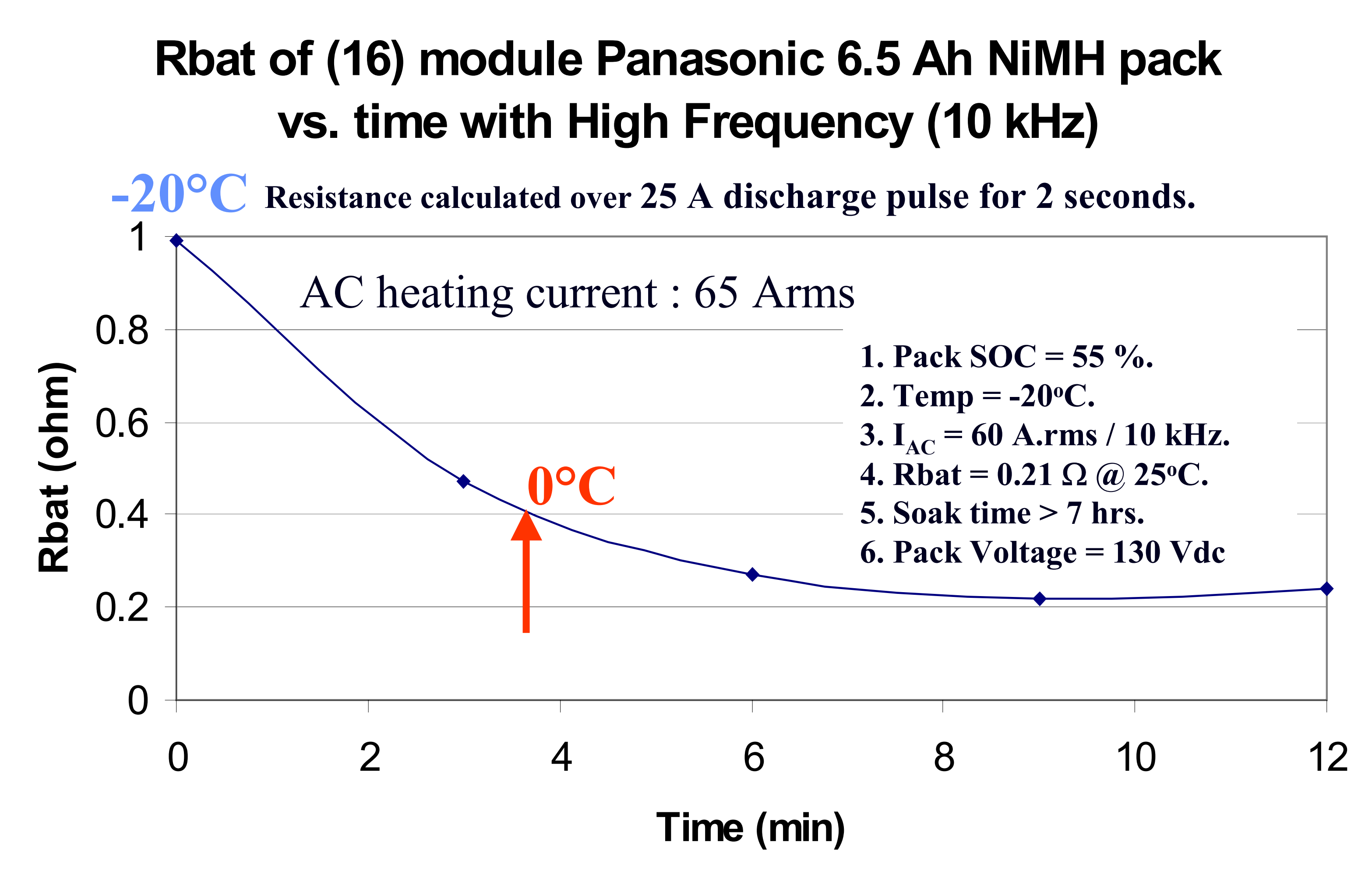




Obtained Battery Internal Resistance for various Temp and State of Charge



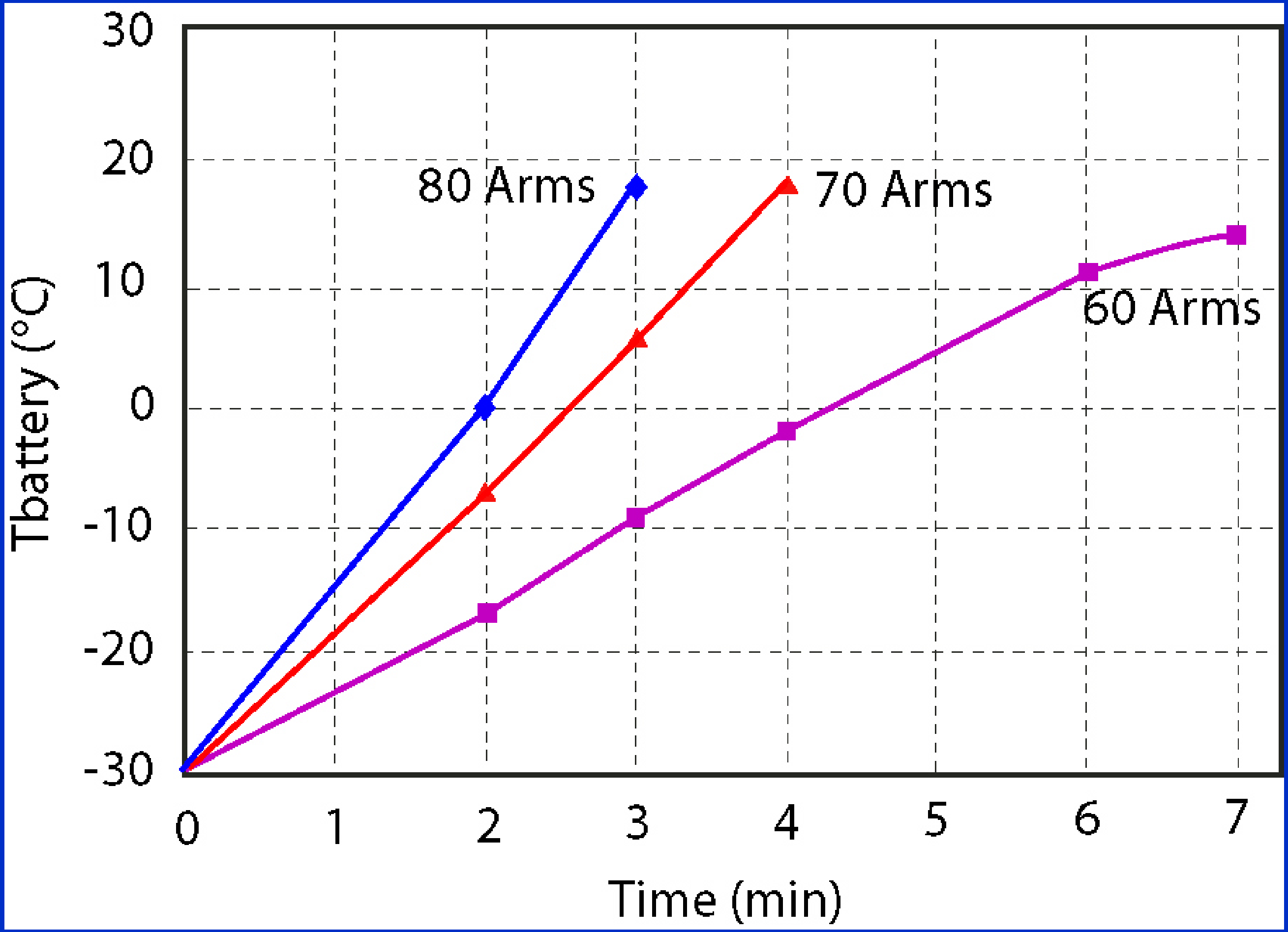
High Frequency AC Heating on the NiMH Pack



T (C)	R Ohm
-20	1.024
-10	0.614
0	0.410
10	0.333
25	0.205
35	0.179

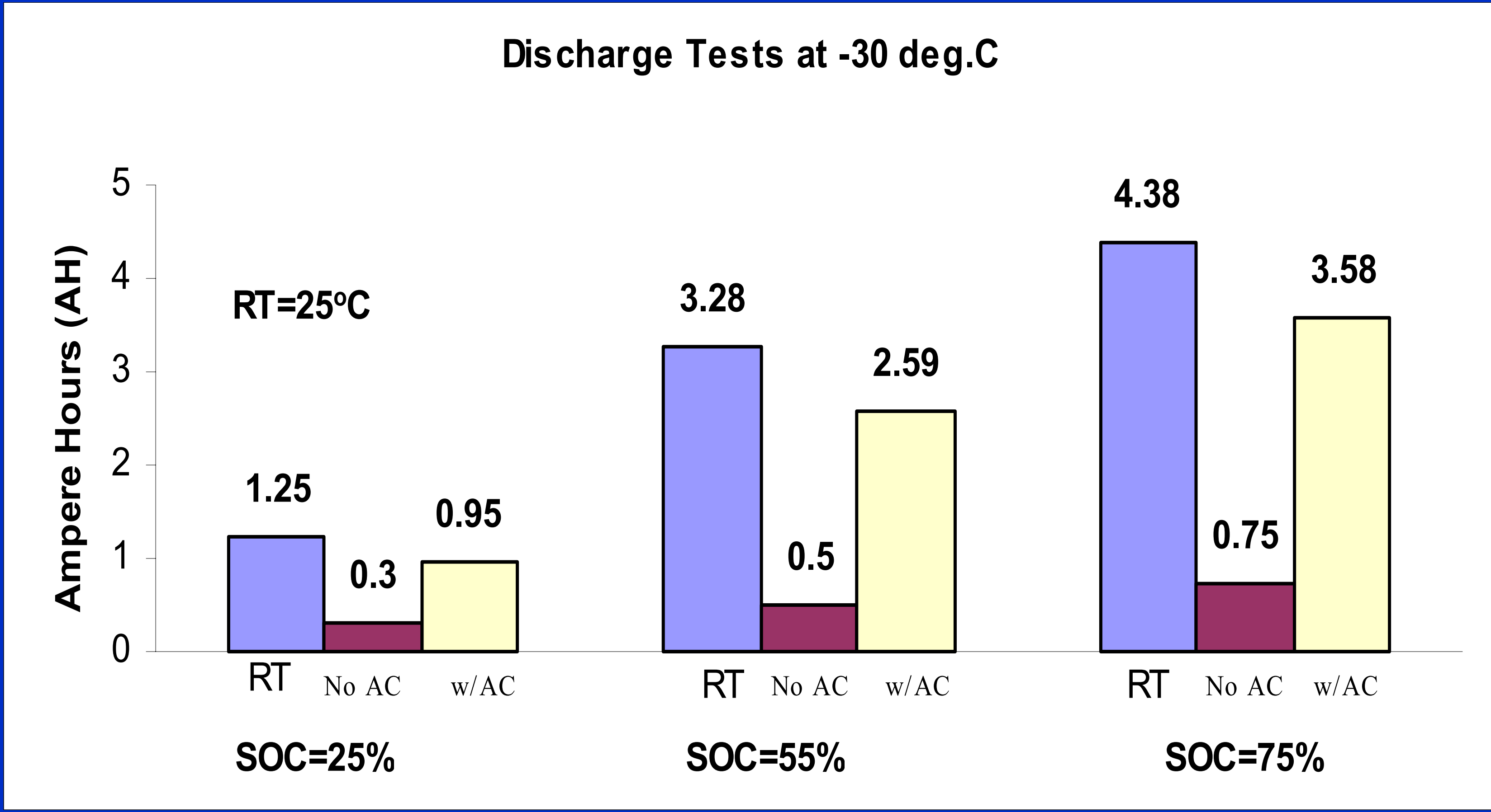
Impact of Higher Current Amplitudes

Frequency = 10 kHz



Battery Capacity Improves with AC Heating

Frequency = 10 kHz



Concluding Remarks

- Battery thermal management necessary in HEVs
- Analysis showed that core heating is the most effective method to preheat batteries
  - Uses least amount of energy for the same Temp rise
  - More uniform temperature distribution
- Testing showed that core heating is feasible through applying AC power through battery terminals
- Further analysis, testing, hardware evaluation, and trade off analysis under way for on-board vehicle applications.