Thermal Characterization of Selected EV and HEV Batteries

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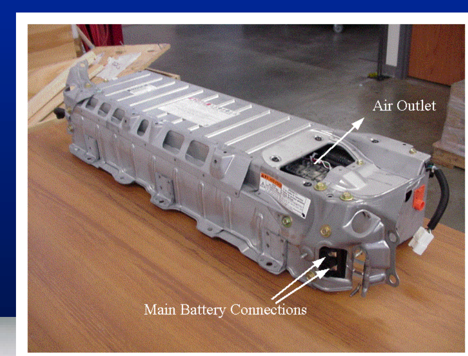
Presentation Outline

- Background
  - – The need for thermal characterization
- Heat Capacity
- Heat Generation
- Thermal Imaging
- Concluding Remarks

Background

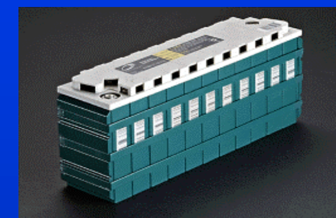
- Electric and hybrid electric vehicles in the market place

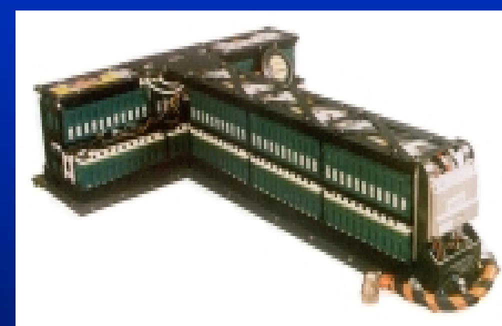
- HEV success depends on battery performance, life, and cost



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





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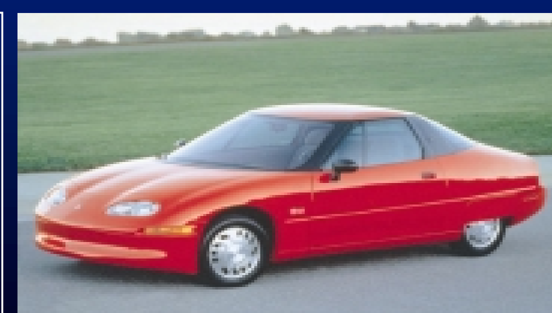
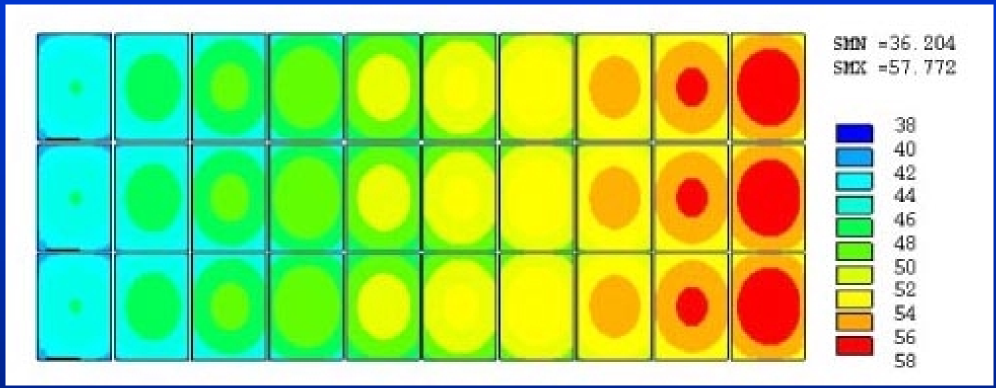
Battery temperature affects vehicle performance, reliability, safety, and life cycle cost



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

NREL Created Capabilities for Battery Thermal Management

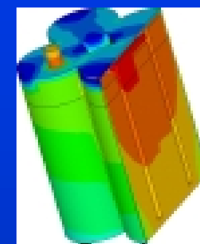
- Thermal analysis (CAD) for proper design, evaluation, and packaging

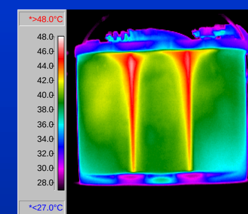
  Thermal imaging for evaluation and diagnostics

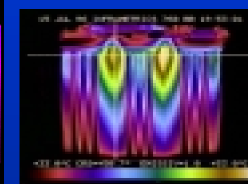
- Fluid and heat transfer experiments for uniform temperature distribution and low parasitic power designs

  Thermal characterization for heat generation and heat capacity

- Battery modeling for vehicle simulation







Thermal Characterization

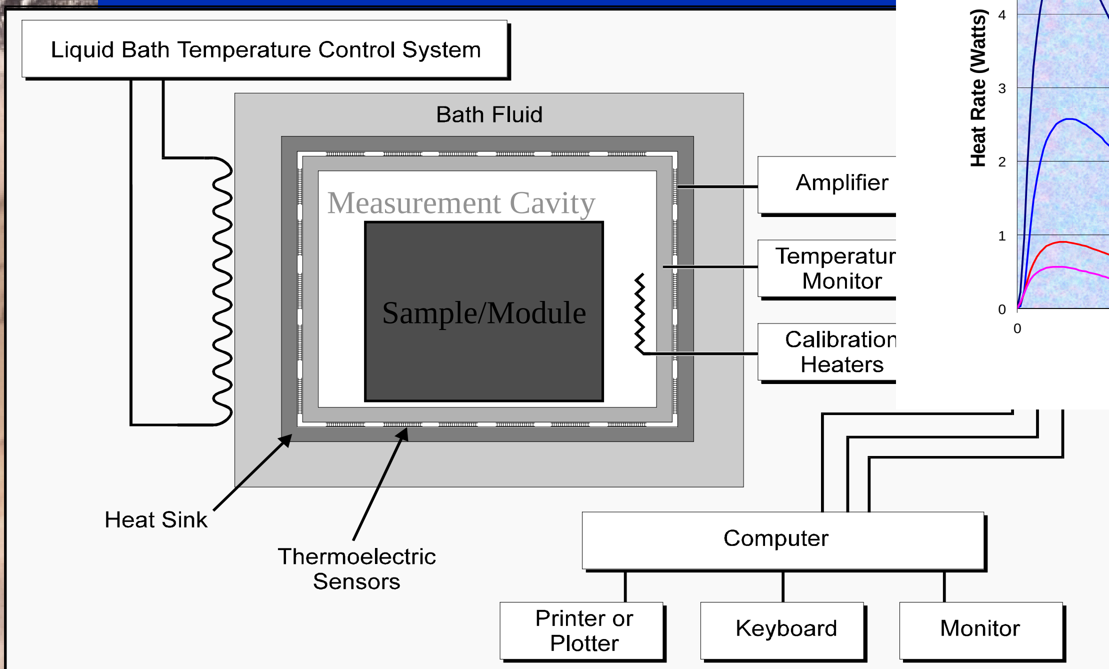
- Designing and evaluating battery thermal management systems requires knowledge of **heat generation** from full-size modules and their **heat capacity**
- A large size calorimeter was needed

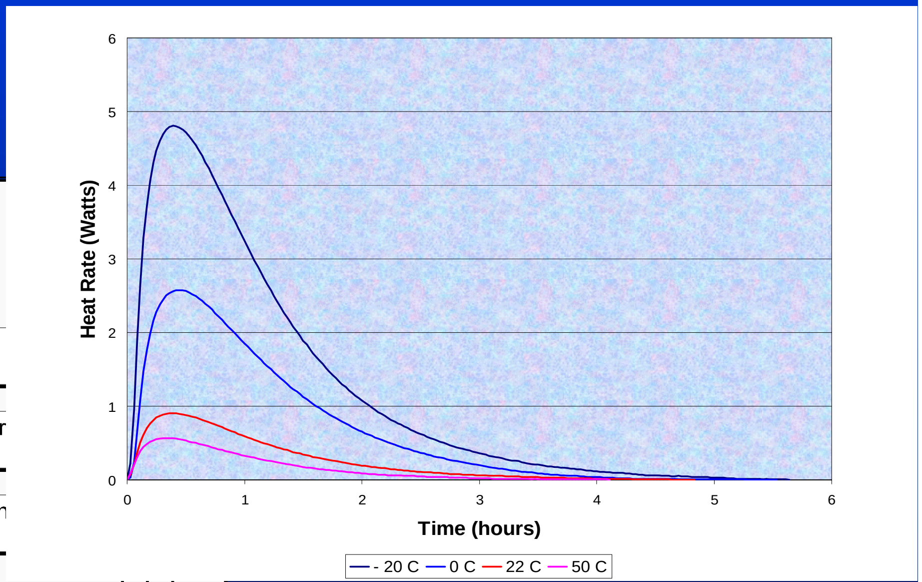
- Cavity dimensions: 21 cm x 20 cm x 39 cm (WxHxL)
- Heat rate detection: 0.015 W to 100 W
- Minimum detectable heat effect: 15 J (at 25ºC)
- Baseline stability: ± 10 mW
- Temperature range: -30ºC to 60ºC (±0.001°C)

Calorimeter Cavity

Calorimeter Design and Response

- Single-ended heat conduction type
- Heat flux measured between the sample and a heat sink

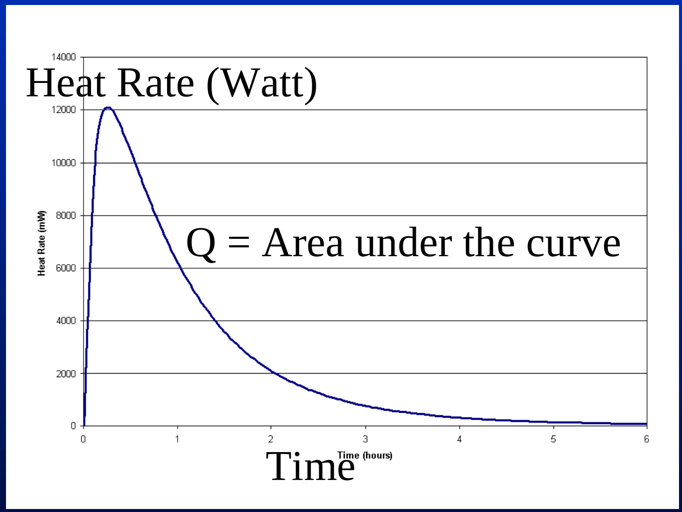




- The heat sink is kept at a constant temperature

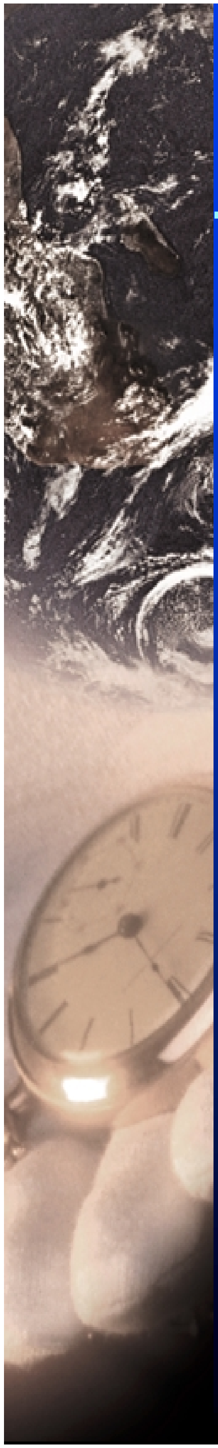
Heat Capacity

- Amount of heat required to cool or heat 1 kg of a material by 1°C
- Depends on the constituents of the module
- The heat lost/gained (Q) from the battery going from Tinitial to Tfinal is measured by calorimeter



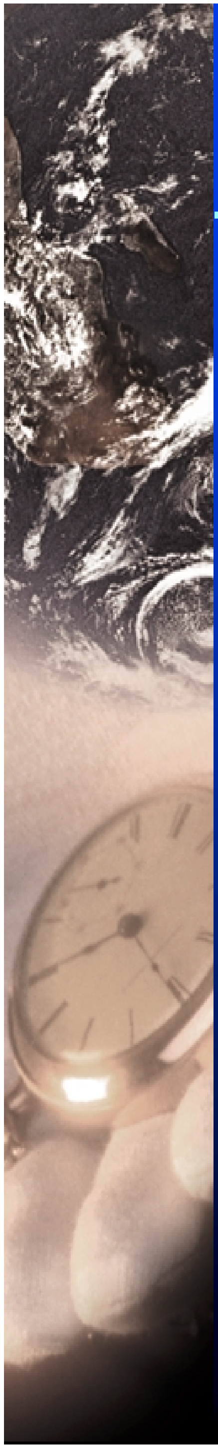
- Heat capacity is calculated by

$$C_p = Q/\ m^*\ (T_{initial} - T_{final})$$



Typical Heat Capacity of EV/HEV Batteries

Battery type	Application	Average Temp (°C)	Heat Capacity J/kg/°C
NiMH – 18 Ah	HEV	33.2	677.4
Li-Ion - 6 Ah	HEV	33.1	795
Li-Ion Polymer – 4 Ah	EV	18	1011.8
NiMH – 90 Ah	EV	33.9	787.5
NiMH – 6.5 Ah	HEV	19	810
VRLA – 16.5 Ah	HEV	32	660
Ni-Zn – 22 Ah	EV	19.95	1167



Heat Generation

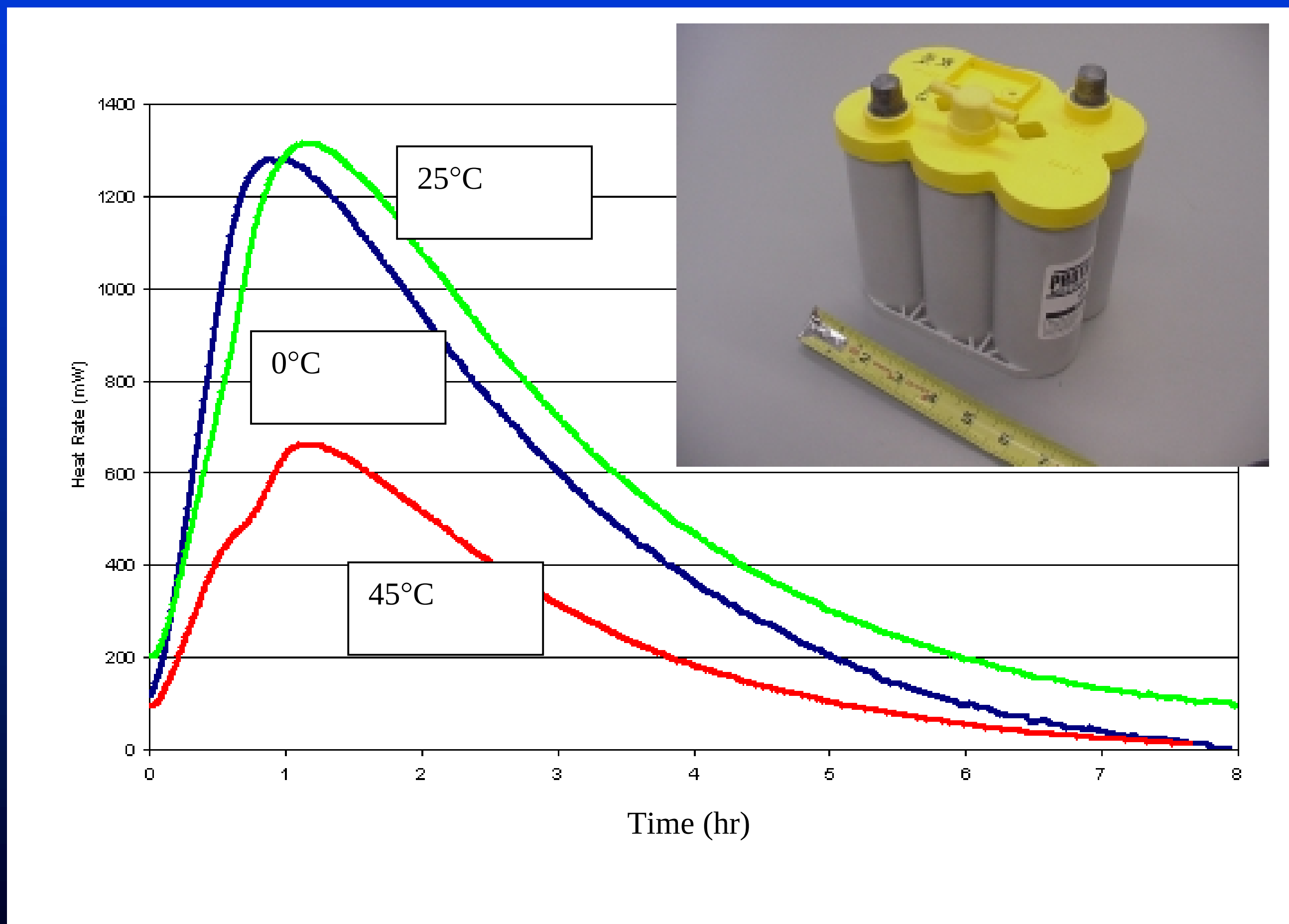
- Battery heat generation depends on several factors
  - Chemistry
  - Construction
  - State of charge
  - Direction of current
  - Temperature
  - Charge or discharge rate and profile
- Sources of heat
  - Electrochemical reactions– enthalpy change (+ve or –ve)
  - Resistive heating – I^2R heating (always +ve)

Measuring Heat Generation

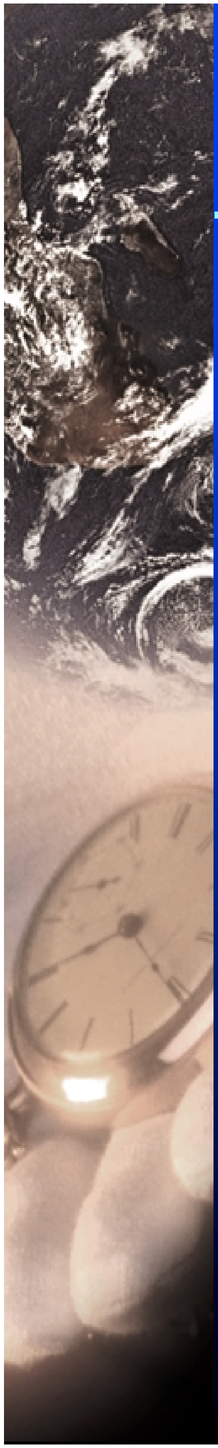
- A module with known capacity is placed in the calorimeter
- The module is brought in thermal equilibrium with the calorimeter cavity temperature
- The module is charged/discharged with battery cyclers
- Thermal equilibrium is achieved again
- Heat rate measured by the calorimeter is corrected
  - Ambient temperature changes
  - Self discharge
- Corrected heat rate is integrated versus time to give heat generation rate

Heat from Optima VRLA HEV Module

Heat generation rate from C/1 discharging of a fully charged Optima module

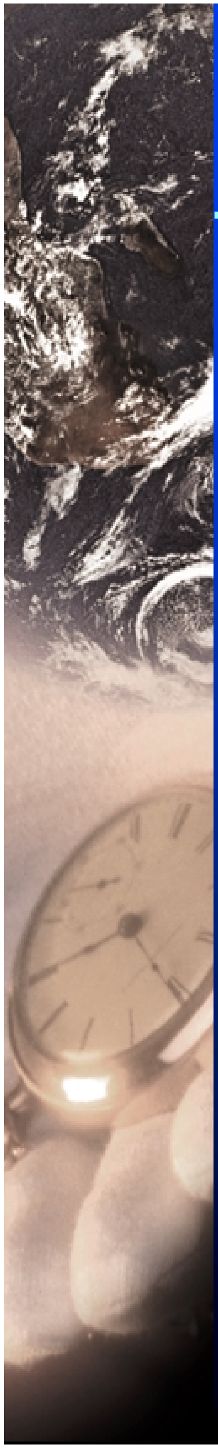


T (°C)	P (W)
0	7.27
25	7.7
45	2.4



VRLA Heat Generation Increases with C Rate

Cycle	Discharge/ Charge Capacity (Ah)	Initial Temp. (ºC)	Efficiency (%)	Average Heat Rate/Module (W)
C/2 Discharge	10.58	0	95.2	4.69
C/1 Discharge	8.47	0	96.3	7.27
2C Discharge	6.60	0	94.2	22.3
5C Discharge	4.48	0	89.6	96.4
Recommended Charging Scheme after C/1 Discharge	8.62	0	83.2	9.88



VRLA Heat Generation Generally Decreases with Temperature

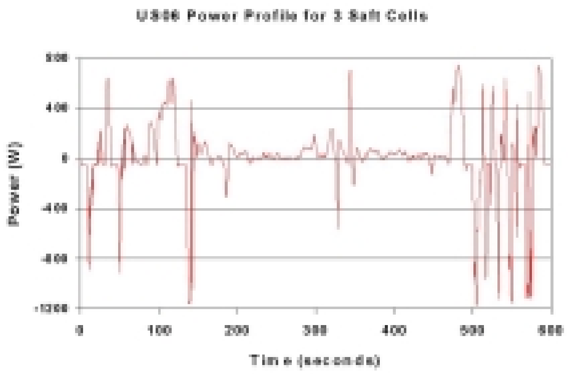
Cycle	Discharge/ Charge Capacity (Ah)	Initial Temp. (ºC)	Efficiency (%)	Average Heat Rate/Module (W)
C/2 Discharge	10.58	0	95.2	4.69
C/2 Discharge	11.71	25	96.9	3.02
C/2 Discharge	14.48	45	98.2	1.9
5C Discharge	4.48	0	89.6	96.4
5C Discharge	7.12	25	91.1	84.1
5C Discharge	9.29	45	92.9	67.2

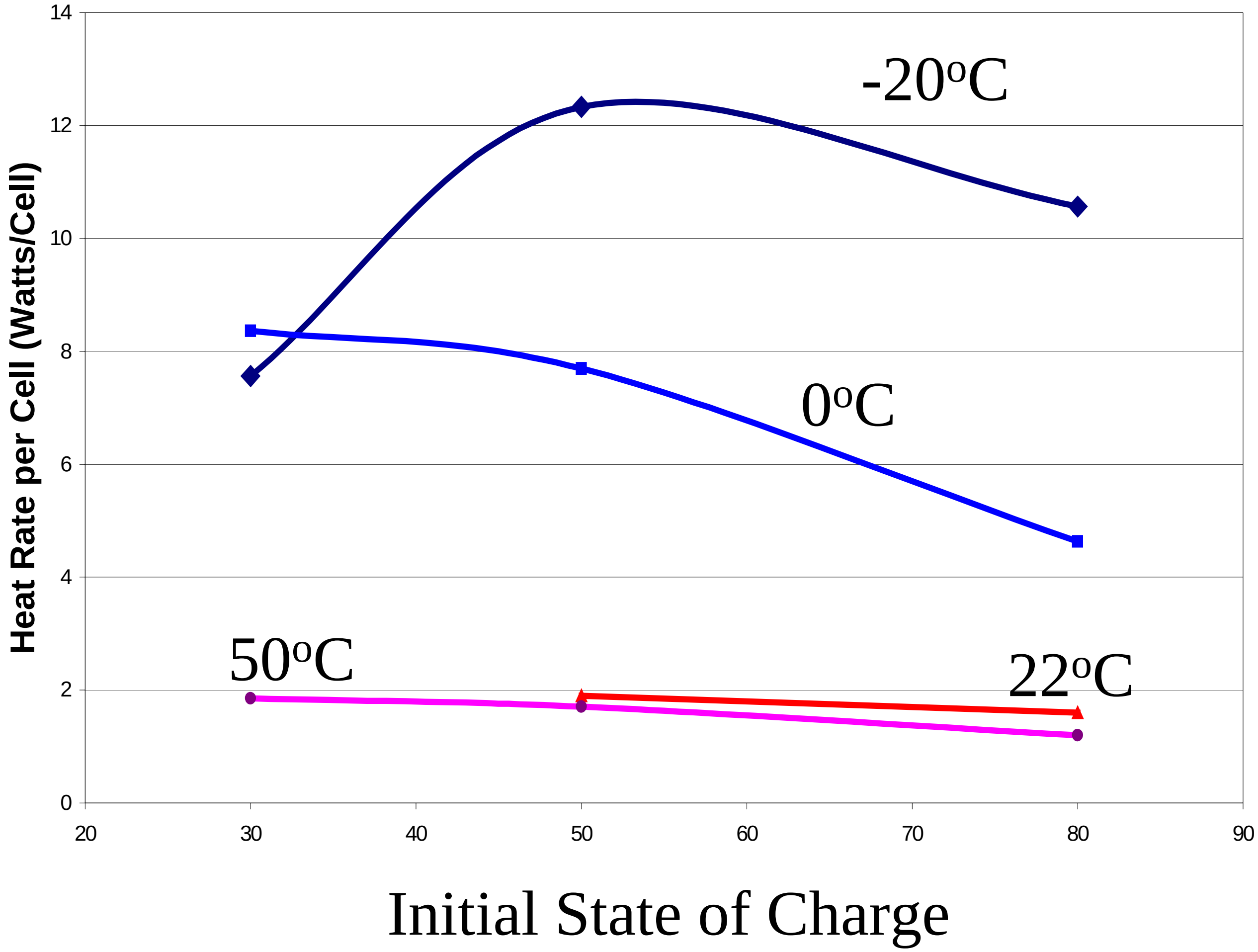
Heat Generation from a Ni-Zn EV Module

Higher heat generation with higher C rate and battery temperature.

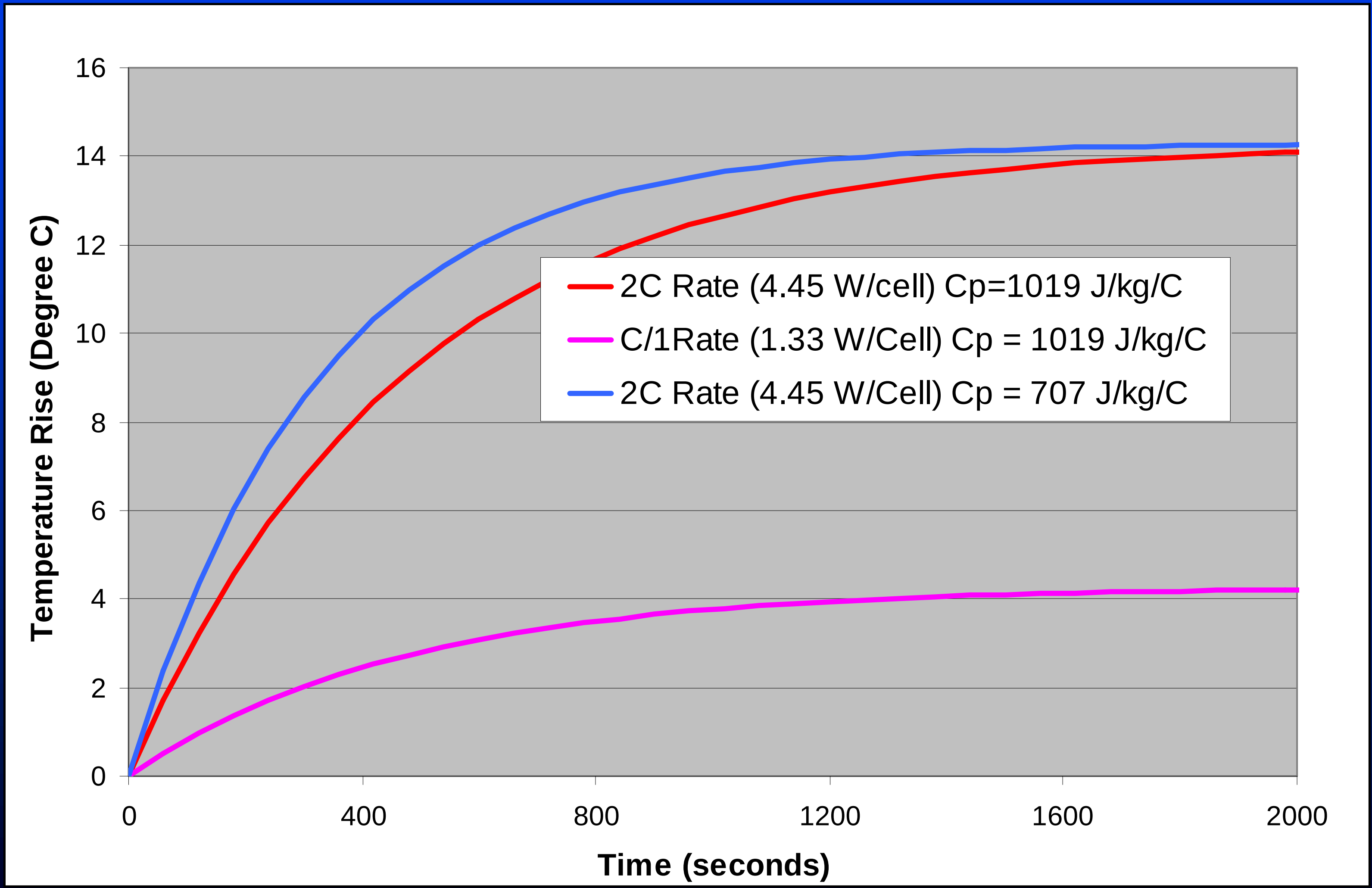
Cycle	Discharge Capacity (Ah)	Initial Temperature (ºC)	Average Heat Rate/Module (W)
C/3 Discharge	24.9	25	16.2
C/2 Discharge	24.7	25	25.7
C/1 Discharge	23.5	25	57.1
5C Discharge	23.4	25	488.4
C/2 Discharge	19.74	0	30.49
C/1 Discharge	15.57	0	74.65

Heat Generated from a Li-Ion HEV Module under US06 Driving Profile

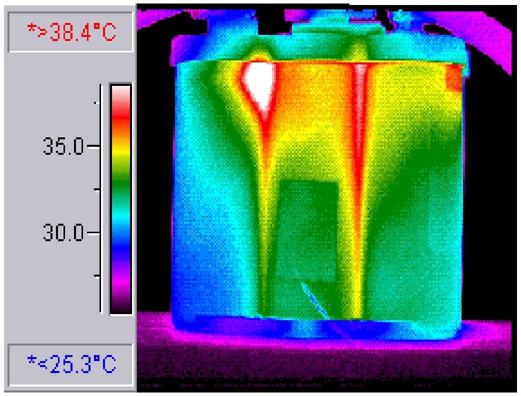




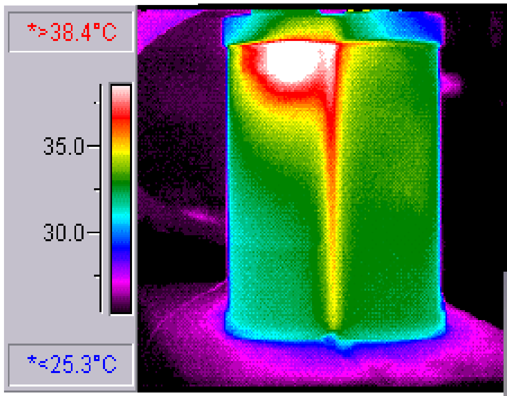
Impact of Heat Generation Rate and Heat Capacity on a Module Temperature Rise



IR Thermal Imaging Provides Insight on Thermal Behavior of Module

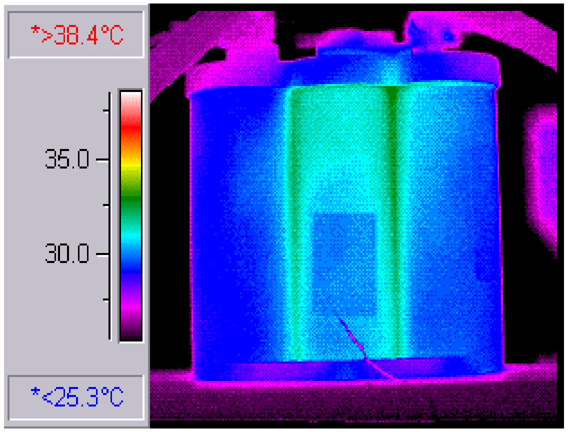


a) Face at end of charge.

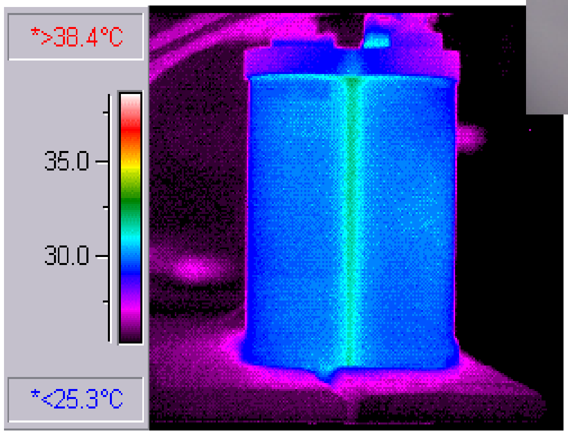


b) Side at end of charge.

VRLA Module



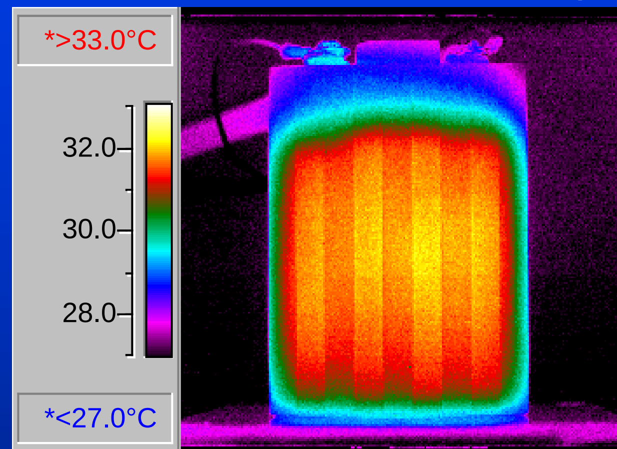
c) Face at end of 2C discharge.

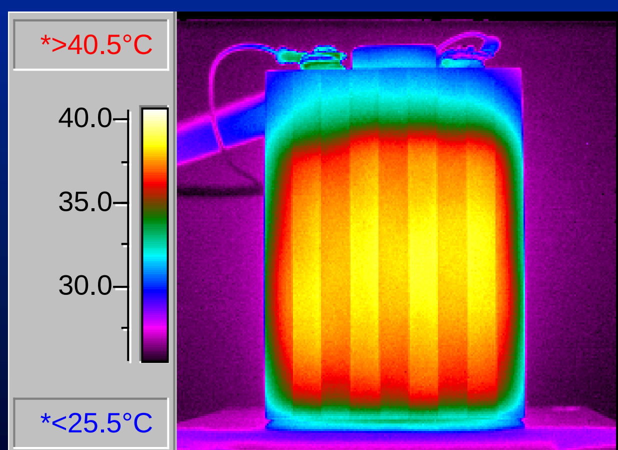


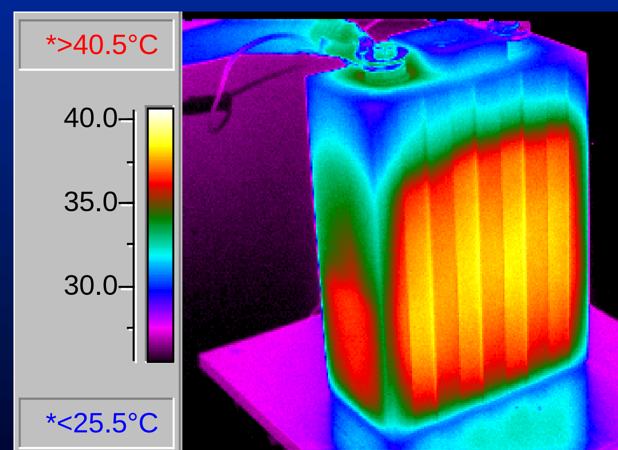
d) Side at end of 2C discharge.

Thermal Images of Ni-Zn Module

Face at end of C/3 Discharge

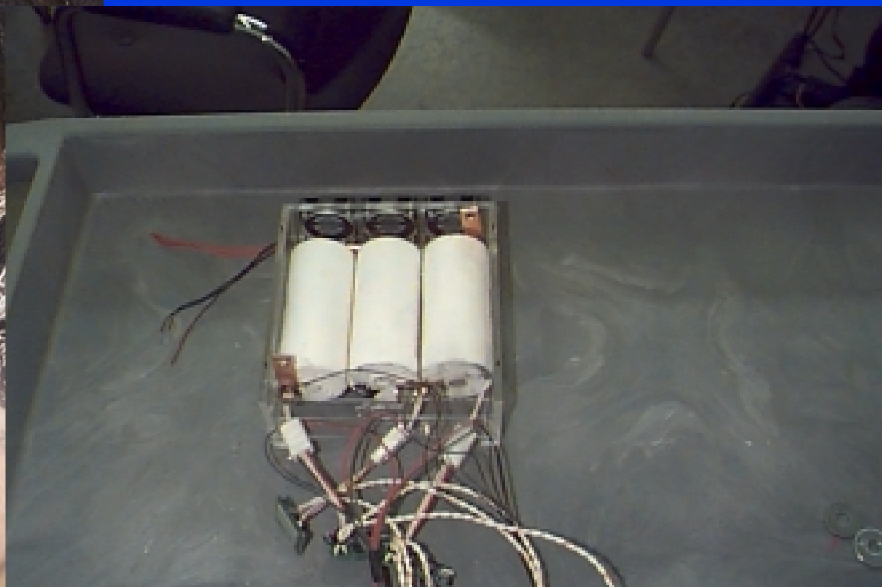




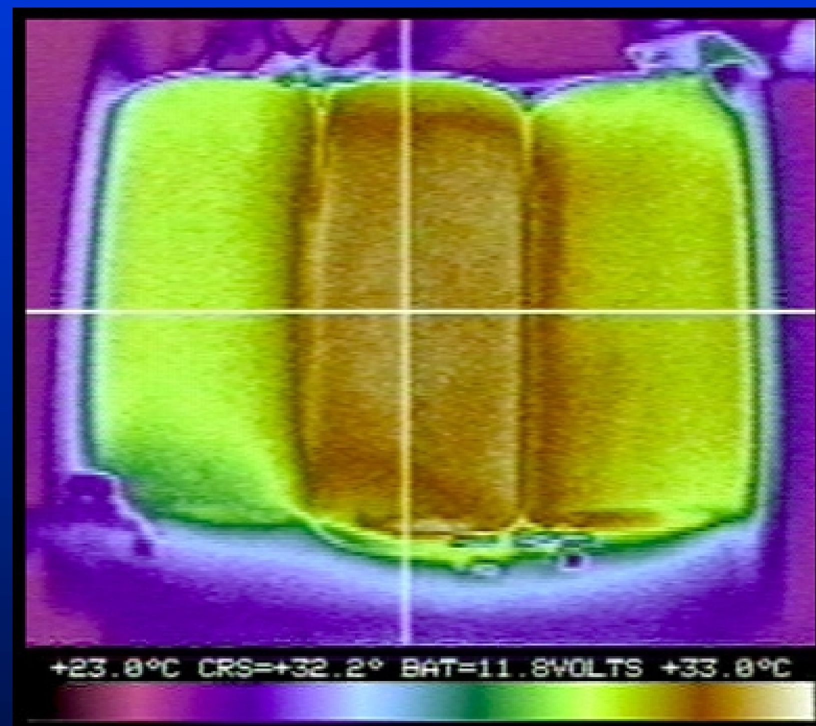


At end of C/1 Discharge

Thermal Images of Li-Ion Cells



- More uniform temperature distribution
  - Conductive materials
  - Terminals at both ends
  - Lower thermal mass



Only 2^{o}C temperature difference

Concluding Remarks

- Thermal management of EV and HEV batteries required.
- Thermal characterization of batteries needed to design of EV and HEV battery thermal management system.
- Heat capacity and heat generation of selected HEV and EV modules were measured.
- IR thermal imaging a visual diagnostic tools

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