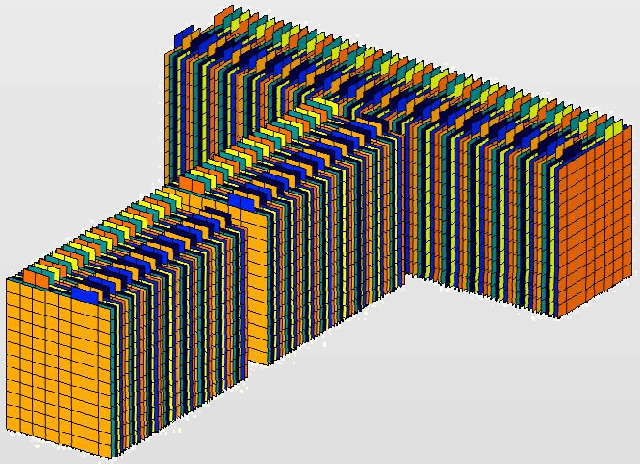
ThermoAnalytics®

Total Thermal Solutions

RadTherm Battery Modeling
UGM 2011- Antti Jussila

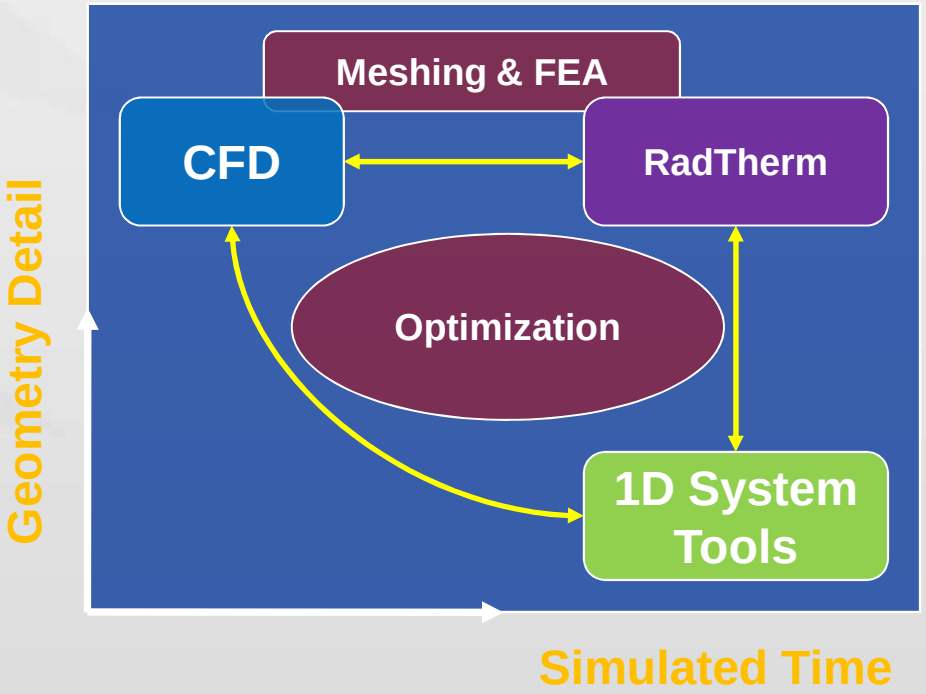
Agenda

- Battery Design Issues
- Physical Description
- Model Description
  - Approach
  - Implementation
- Model Inputs
- Development Status



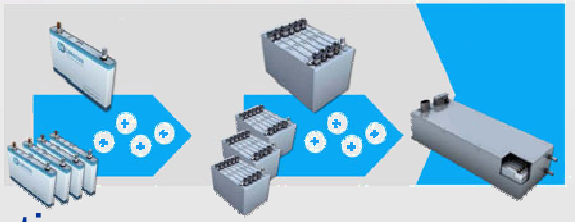
RadTherm Battery Simulation

- **1D System Tools**
  - Concept 1D Component Models
  - Long Transients solved quickly
- **RadTherm**
  - Simple 1D, 2D or Detailed 3D Geometry
  - Radiation, Conduction, Convection
  - Long Transient
  - Rapid Trade Studies
- **CFD**
  - Highly Detailed 3D Geometry
  - Complex Flow
  - Steady State or Short Transient

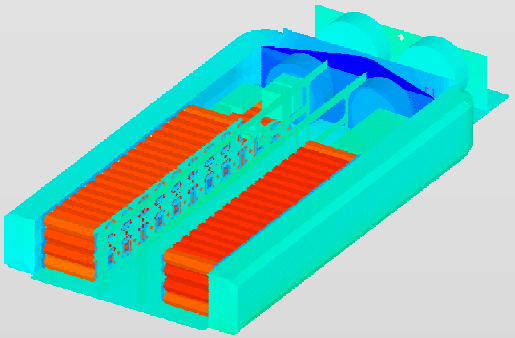


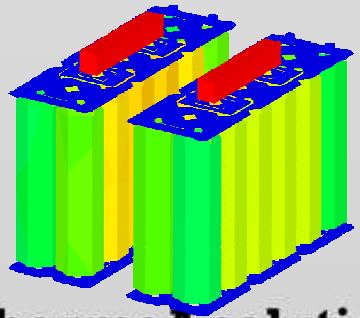
CAE Coupling & Integration
1D Tools – AMESim, Matlab, …
CFD – Fluent, PowerFLOW, STAR-CCM+, …
Optimization – Isight, modeFRONTIER, …
Meshing – ANSA, Hypermesh, PowerDELTA,
FEA – ABAQUS, NASTRAN

Thermal Issues



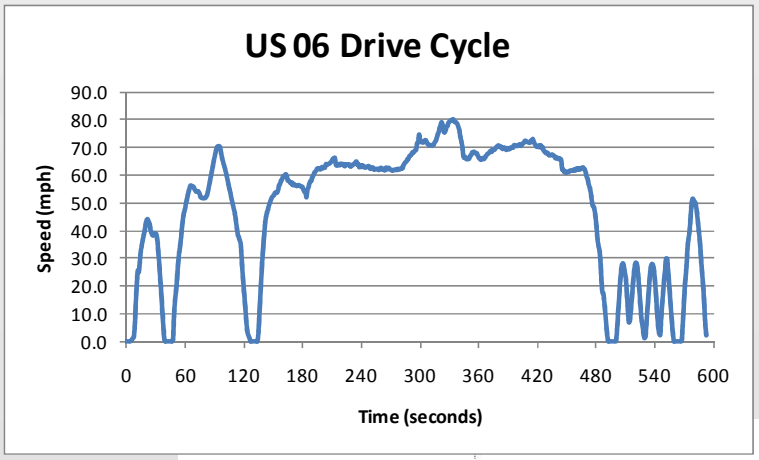
- Battery Cells, Packs & Systems
  - Cells – uniform current, temperature distribution
  - Packs – uniform cooling, environmental effects
  - Systems – Cell balance, SOC estimation
- Cooling Strategies
  - Air (dedicated or shared)
  - Liquid (dedicated or shared)
  - Heat sink, cooling plates, heat pipe, ….
- Hybrid & Electric Vehicle Batteries
  - Performance
  - Lifetime & Durability
  - Safety

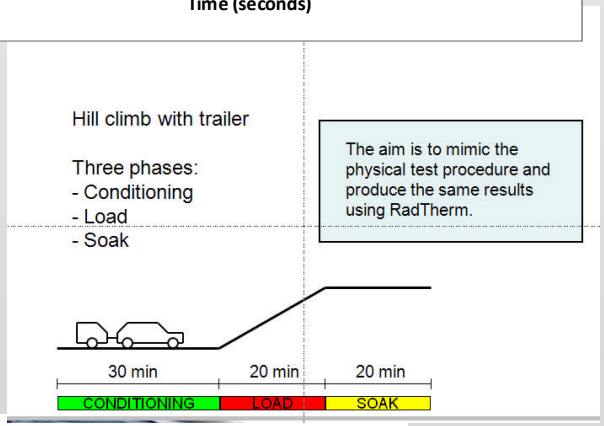


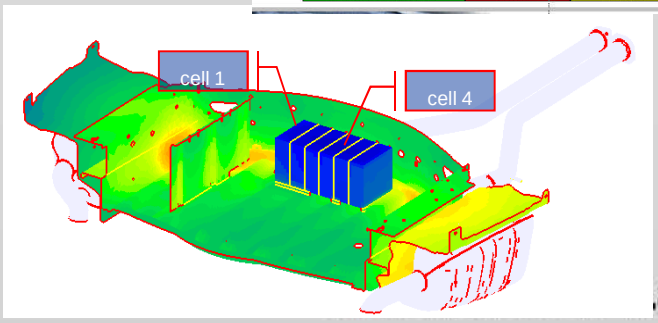


Thermal Scenarios

- Transient
  - Drive Cycles
  - Hot Soak
  - Preheating for Cold Start
  - Load Balancing
  - Abuse Tolerance
  - Cooling System Faults
  - Thermal Runaway

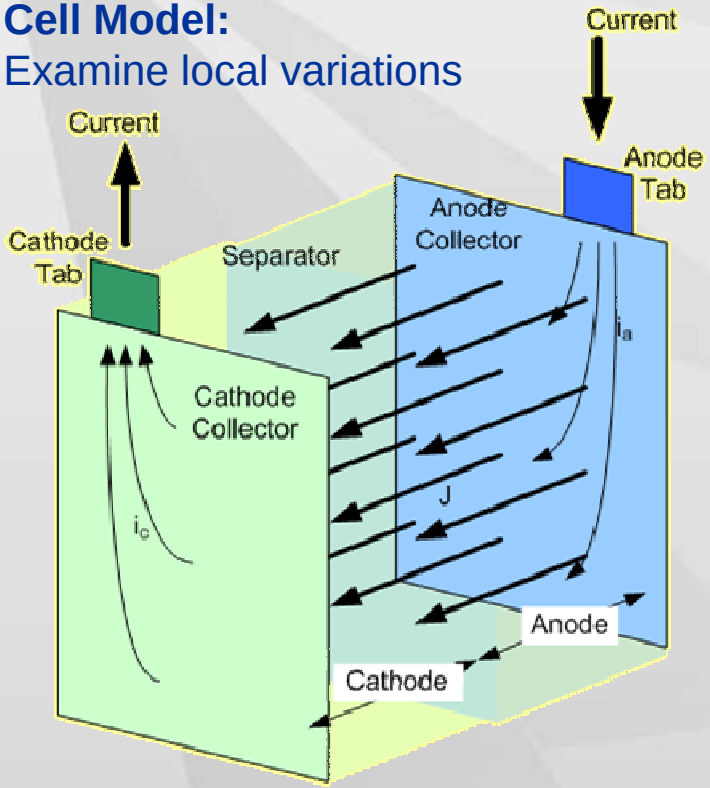






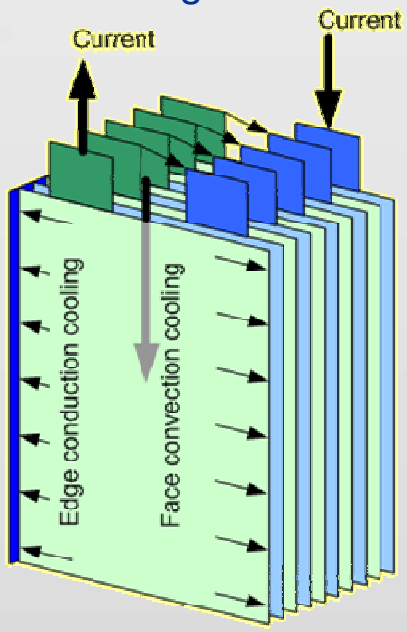
Battery Modeling Description

Cell Model:
Examine local variations



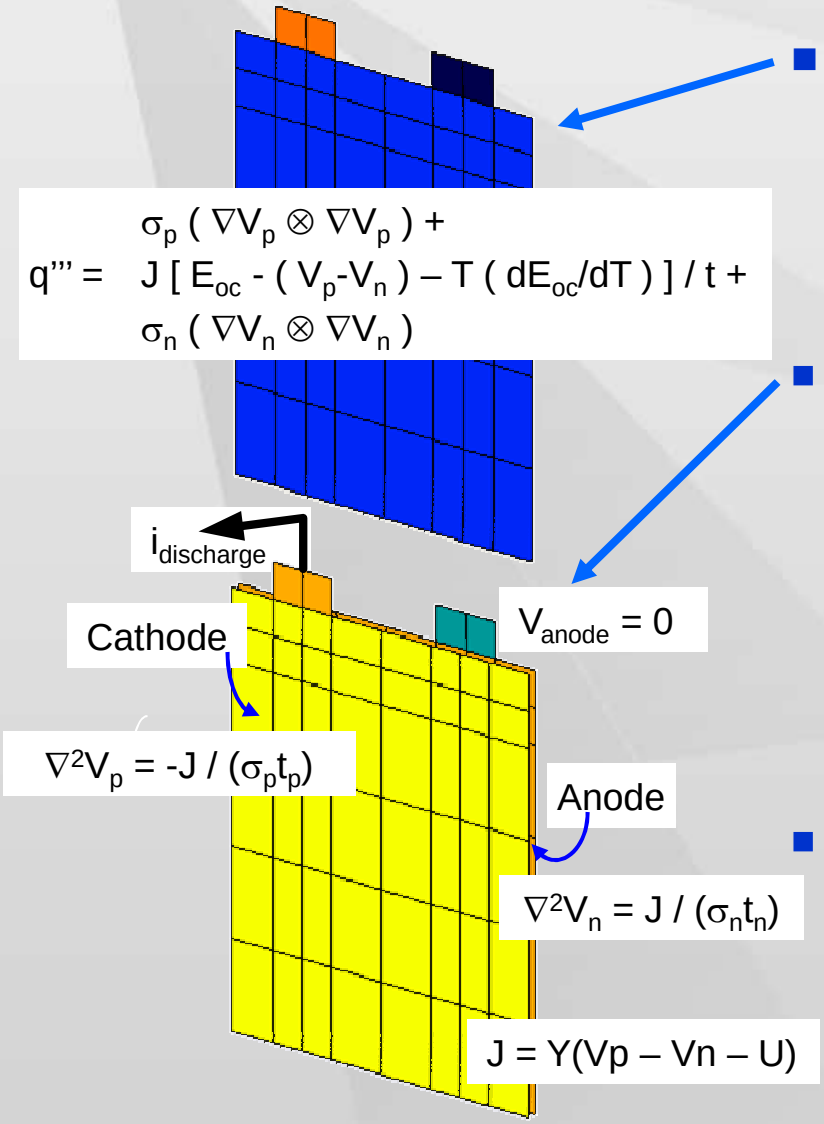
- Effects of tab size/location, cell size, collector thickness:
  - Voltage gradients on collector plates
  - Non-uniform current density
  - Non-uniform ion depletion
  - Non-uniform heating
- Electrical load

Pack Model: examine variations in cell-to-cell average behavior



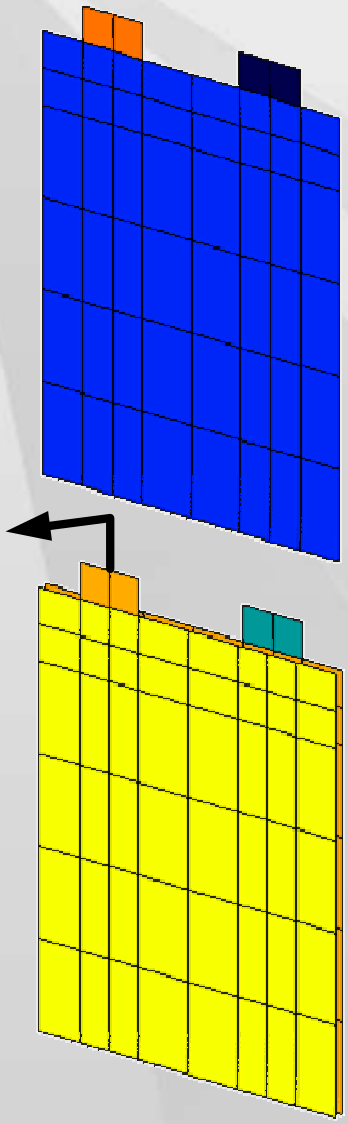
- Effects of pack configuration, flow distribution, packaging:
  - Non-uniform cell behavior
  - Non-uniform cooling
- Effects of electrical load on total thermal load
  - Charge/discharge profile

Battery Model Implemented in RadTherm



- Thermal problem
  - Description of temperature distribution on electrodes
- Electrical problem
  - Description of current density through electrodes
  - Description of voltage distribution on collector plates
  - RadTherm solves thermal analog:
    - Thermal Conductivity = Electrical Conductivity
    - Temperature = Voltage
    - Heat Flux = Current Density
- Two problems coupled via joule heating
  - Calculated in Electrical
  - Imposed on Thermal

Battery Model Setup in RadTherm



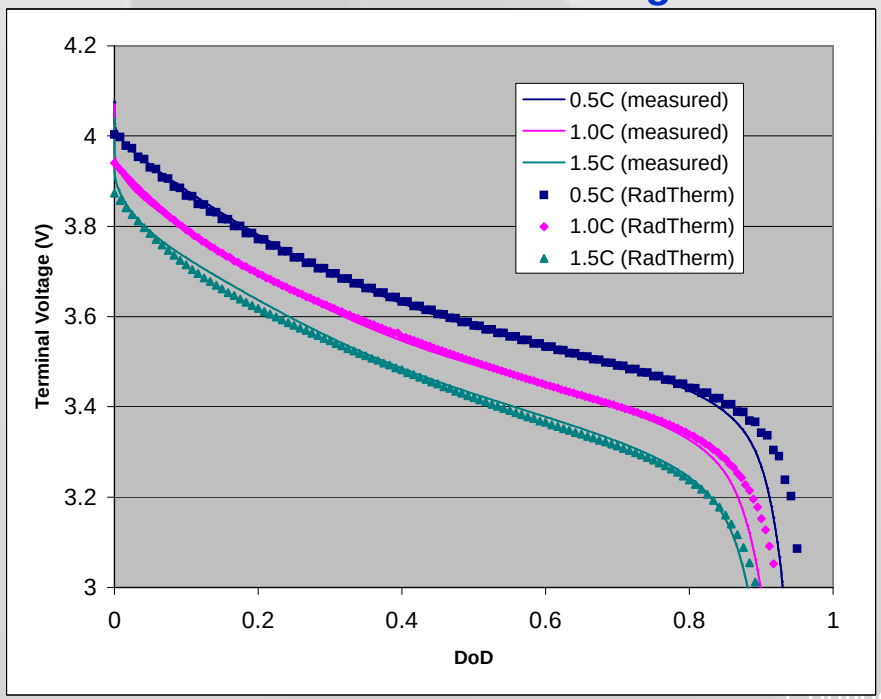
- Thermal problem
  - Cell modeled as multi-layer part
    - Thermal properties of electrodes
    - Convection on front, back face
    - Optional edge conduction
    - Hook function imposes Joule heating derived from electrical model
- Electrical problem
  - Anode, cathode collector plates modeled as standard parts
    - k = electrical conductivity
    - Hook function imposes a ‘heat flux’ equivalent to the current density between electrodes
  - Anode tab is assigned a value of 0 volts (ref voltage)
  - ‘Heat’ equal to discharge current is imposed on cathode tab
  - ‘Temperature’ solution is voltage distribution
- So far, coupling is only one-way
  - Electrical affects thermal
  - Future development will add two-way coupling

Battery Cell Model Validation

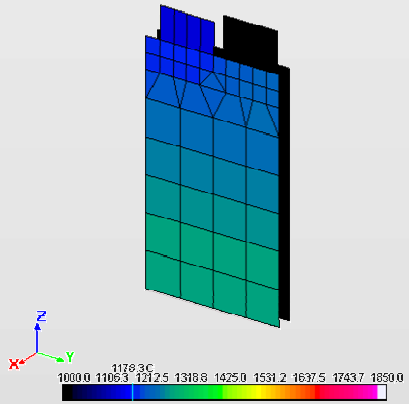
Cell data

Time (sec)	DoDAvg	Cathode Voltage (mV)	Anode Voltage (mV)	Cell Current Density (A/m^2)	Uniformity Index
0	0	4.05E+03	-6.10E-06	-5.38E+02	0
60	0.016	4.03E+03	-6.10E-06	-5.24E+02	0.068
120	0.032	4.00E+03	-6.10E-06	-5.37E+02	0.057
180	0.048	3.98E+03	-6.10E-06	-5.25E+02	0.048
240	0.064	3.95E+03	-6.10E-06	-5.36E+02	0.042
300	0.08	3.93E+03	-6.10E-06	-5.26E+02	0.037
360	0.096	3.91E+03	-6.10E-06	-5.36E+02	0.033
420	0.113	3.89E+03	-6.10E-06	-5.27E+02	0.03

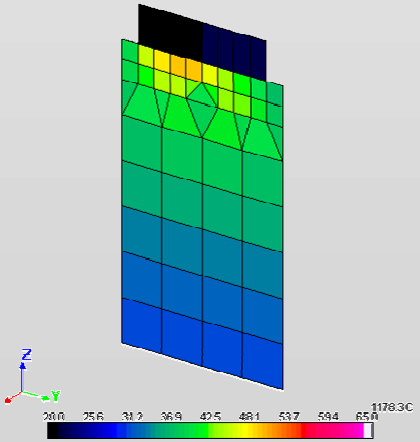
Measured & Simulated discharge curves



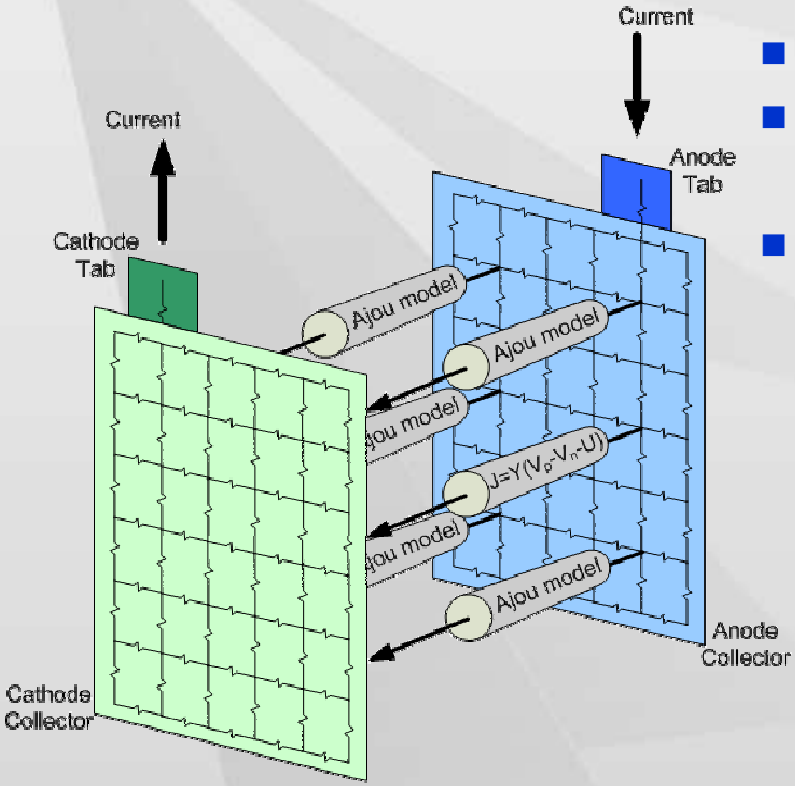
2D Voltage Distribution



2D Temperature Distribution



Ajou Model* Provides Current Density Through Electrodes as Function of Voltage Difference



- Empirical model
- Current Density through Electrodes
- Local current density = function of local potential difference across cell
  - $J = Y (V_p – V_n – U)$
  - V_p = potential on cathode
  - V_n = potential on anode
  - U = fitting parameter (≈ open cell voltage)
    - $U = \Sigma a_i DoD^i$; i=0,1,2,...
  - Y = effective conductivity of cell
    - $Y = \Sigma b_i DoD^i$; i=0,1,2,...
  - DoD = Depth of Discharge
    - $DoD = \int Jdt / Q_T$
    - Q_T = theoretical capacity per unit area
    - DoD varies across electrode area

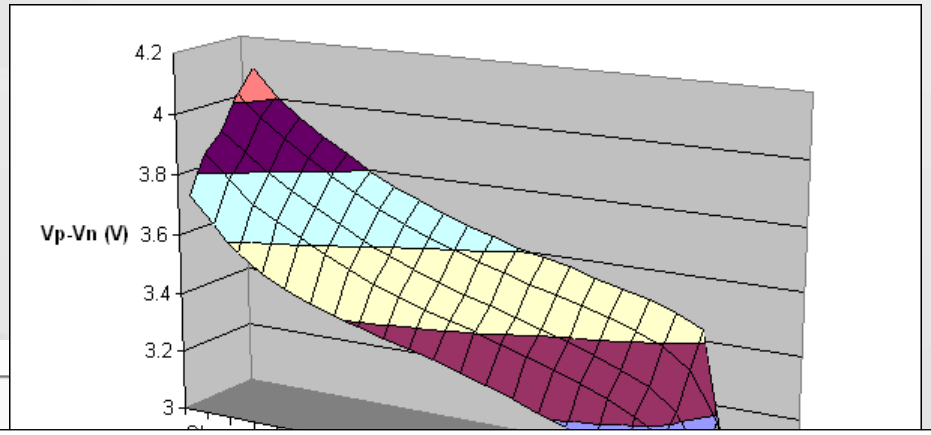
* Also known as NTG model

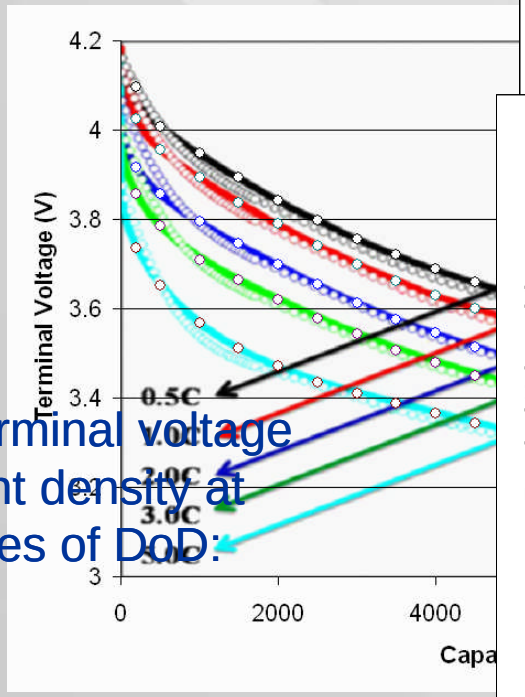
Required Battery Test data

- Data needed to calculate Ajou coefficients
  - Theoretical cell capacity
  - Electrode area
  - Discharge current – 1c, 2c, 4c
  - Voltage data during discharge, correlated to discharge current
    - sufficient to resolve curve at beginning of discharge, end of discharge

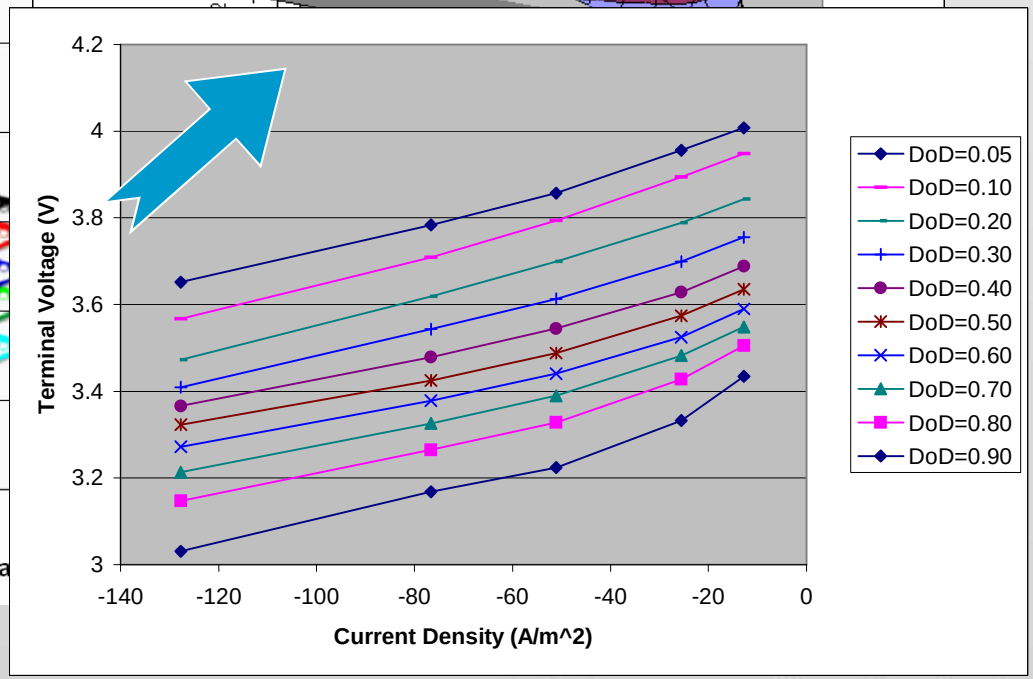
Battery Discharge Data to Coefficients

Obtain terminal voltage versus DoD at different values of current density:

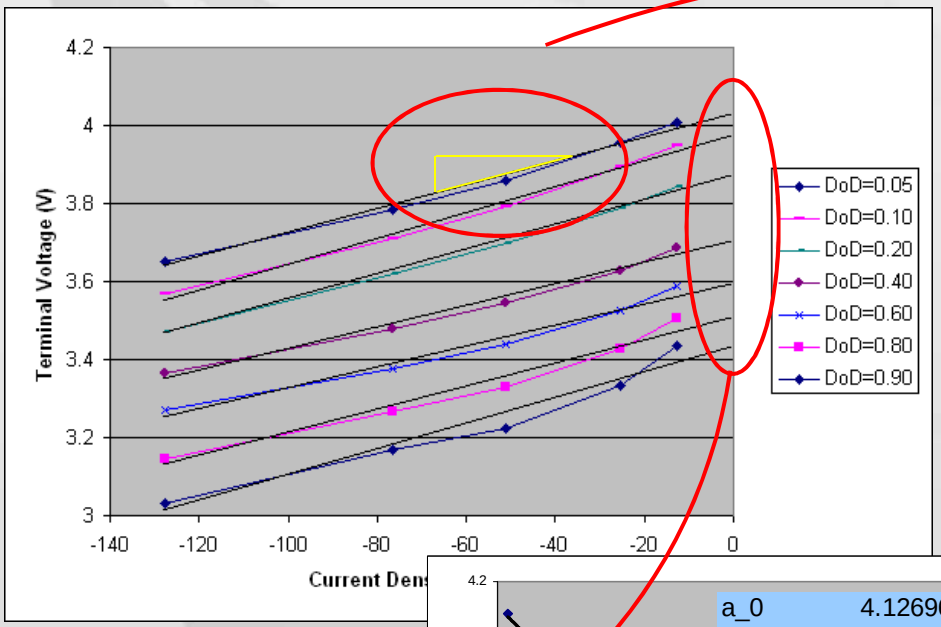




Cross-plot terminal voltage versus current density at different values of DoD:

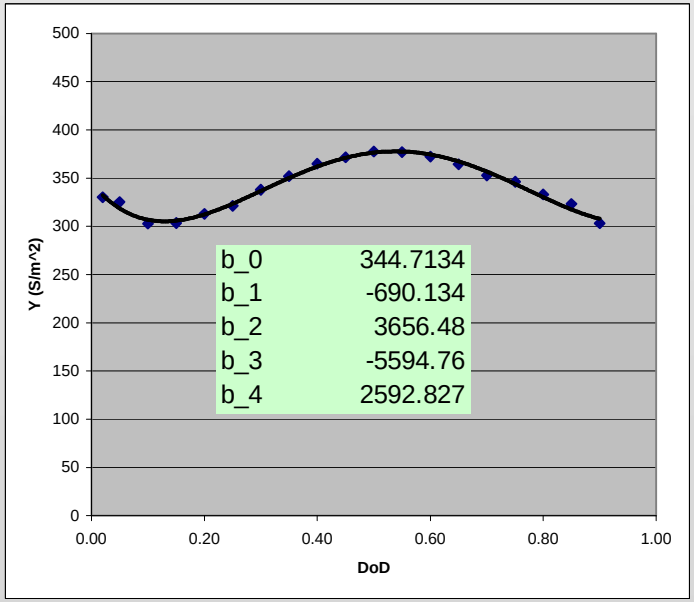


U and Y determined from line fits to data



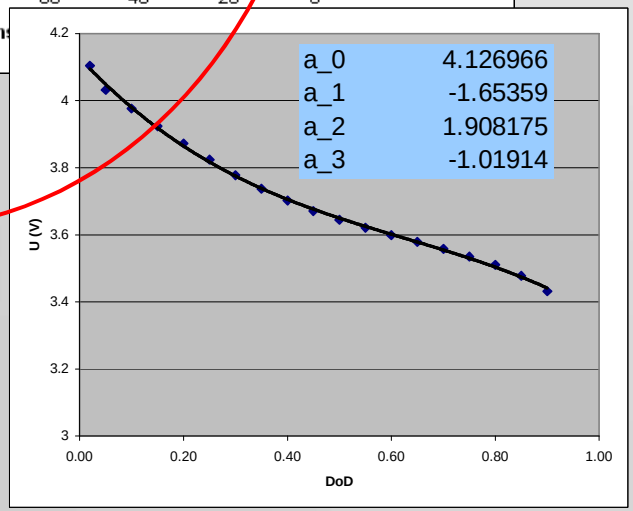
Slope of line is 1/Y

DoD	Y
0.02	330.1501
0.1	302.8415
0.2	312.8386
0.4	364.8562
0.6	372.4626
0.8	333.1441
0.9	303.0941



Y = 344.7 - 690.1DoD + 3656DoD^2 -5595DoD^3 + 2593DoD^4

DoD	U
0.02	4.104145
0.1	3.976391
0.2	3.872191
0.4	3.702418
0.6	3.59893
0.8	3.510945
0.9	3.431629

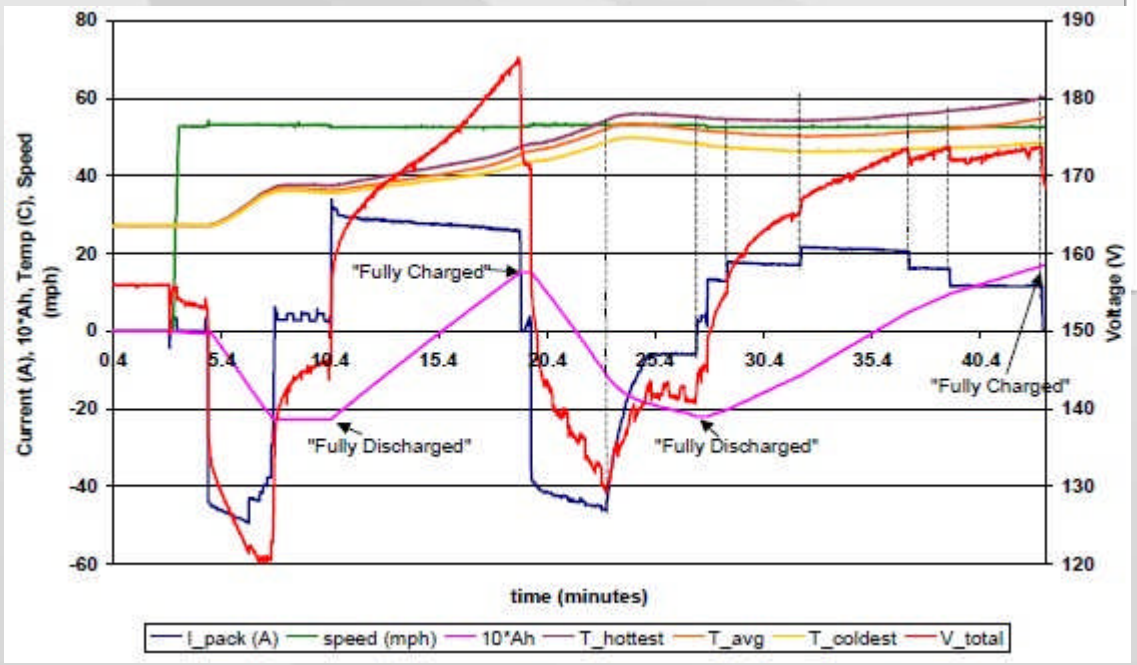


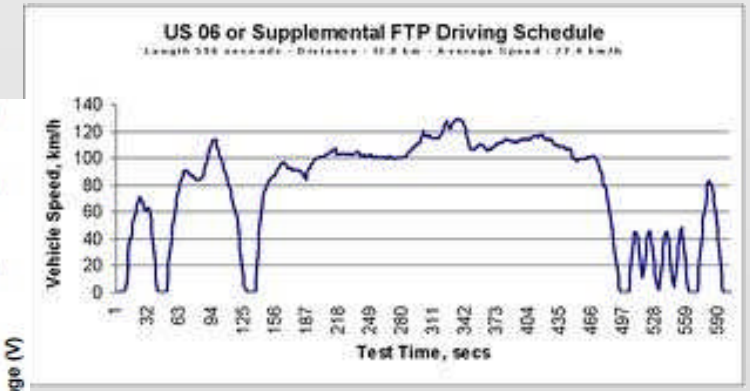
Intercept of line is U

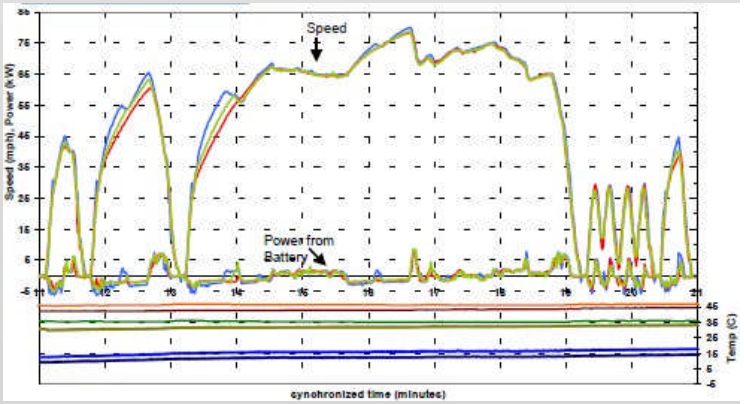
U = 4.127 – 1.654DoD + 1.908DoD^2 -1.0193DoD^3

Next Steps-Drive Cycle - US06

- Transient Current and Voltage inputs

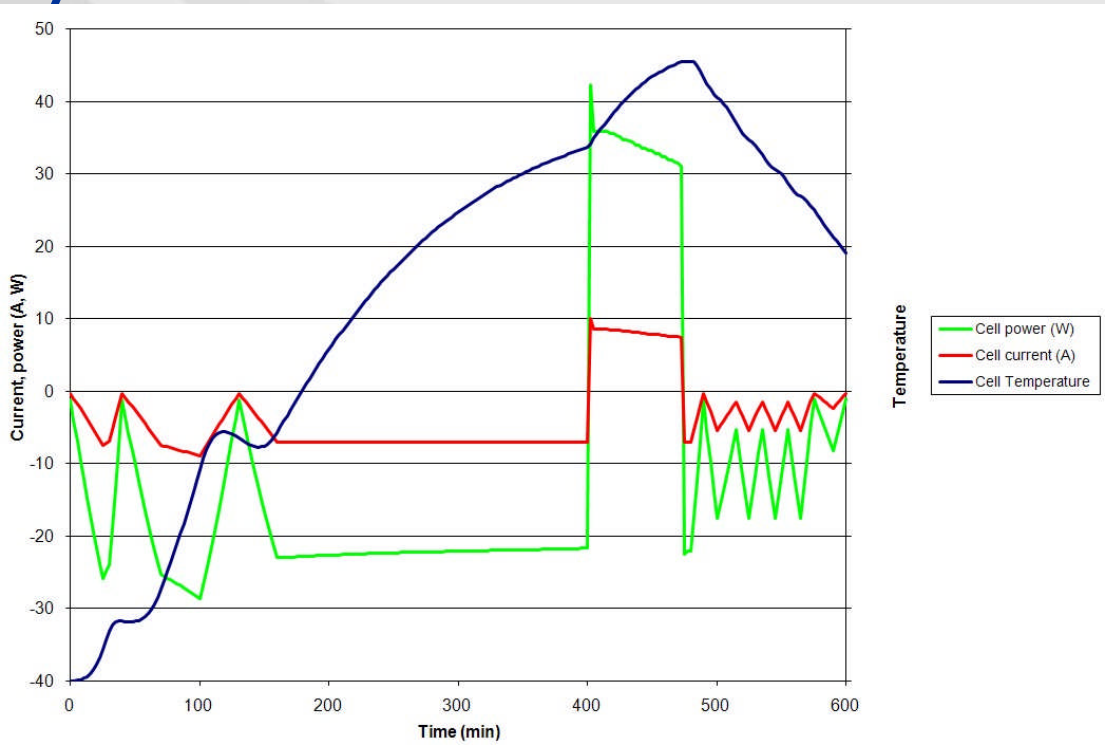






Transient data input-demo example

- Data input from Excel spreadsheet or 1D system tool



- Current input, Temperature output