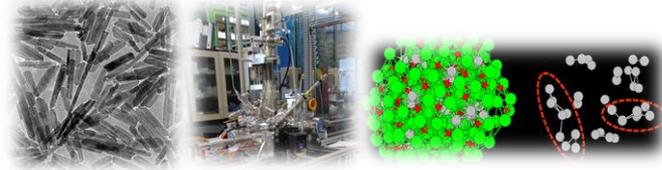


NREL Energy Storage Activities

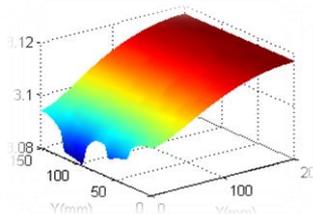
Supporting DOE and industry to achieve energy storage targets for various applications



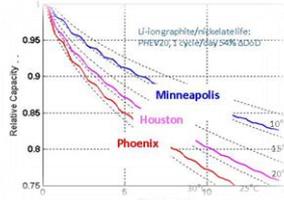
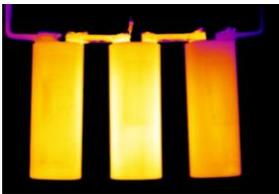
Battery Materials Synthesis and Processing
(Higher energy density and stability)



Component Testing and Characterization
(Evaluate performance, life, and safety)



Multi-physics Battery Modeling
(Improve performance, life, and safety)



Battery Management and Control
(Improve utilization and life)



Battery System Evaluation
(Finding cost-effective pathways)

Thermal Testing: NREL Energy Storage Equipment

Materials Dev., Electrochemical/Thermal Models, Battery Life, Abuse/Safety, Secondary Use, DOE/USABC, CAEBAT

Environmental Testing

Calorimeters

Thermal Conductivity

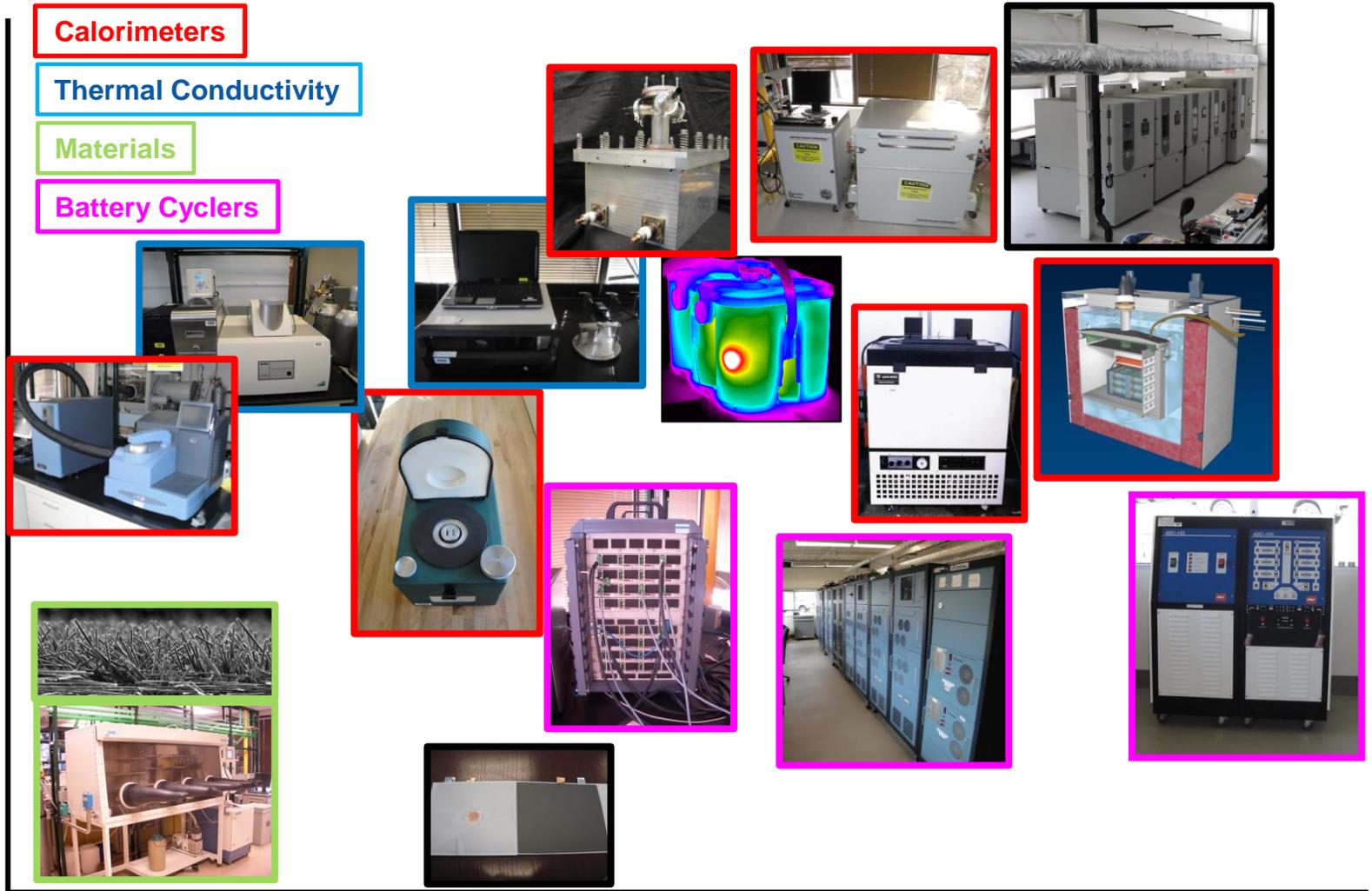
Materials

Battery Cyclers

Thermal Testing

Electrical Testing

Fabrication



Materials

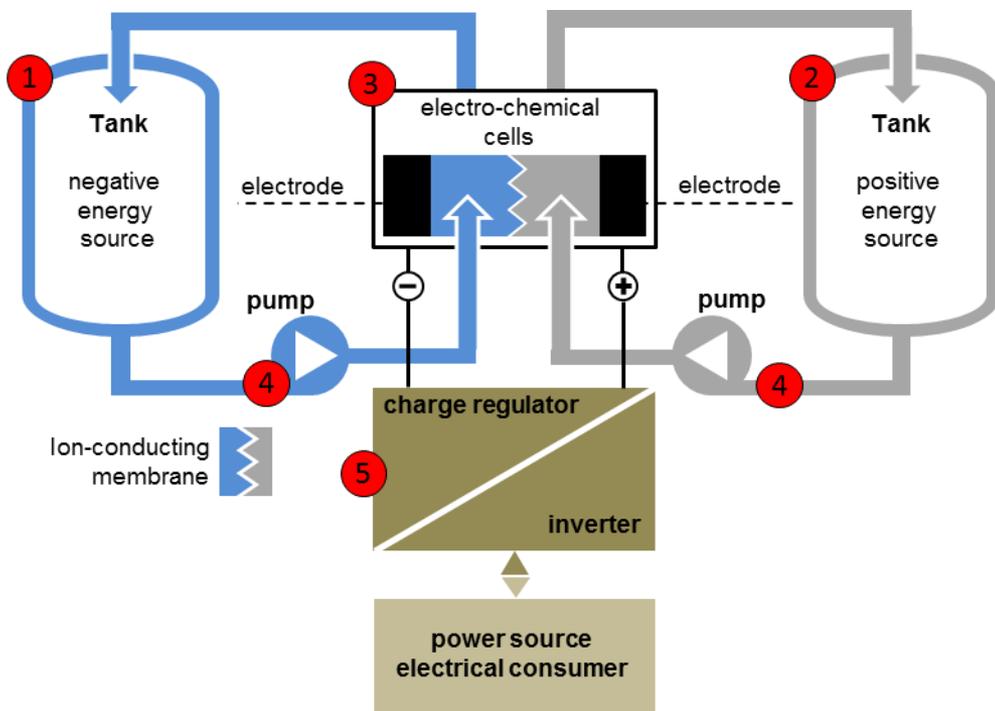
Cells

Modules

Packs

ESIF Testing of American Vanadium Corporation and Gildemeister CellCube

Principles and Features of the CellCube



Main Components

1. Negative storage tank
2. Positive storage tank
3. 2.5kW stacks (energy conversion)
4. Fluid pumps
5. Charge regulators (Dc-links)



CellCube – 20kW/100 kWh

Commissioning

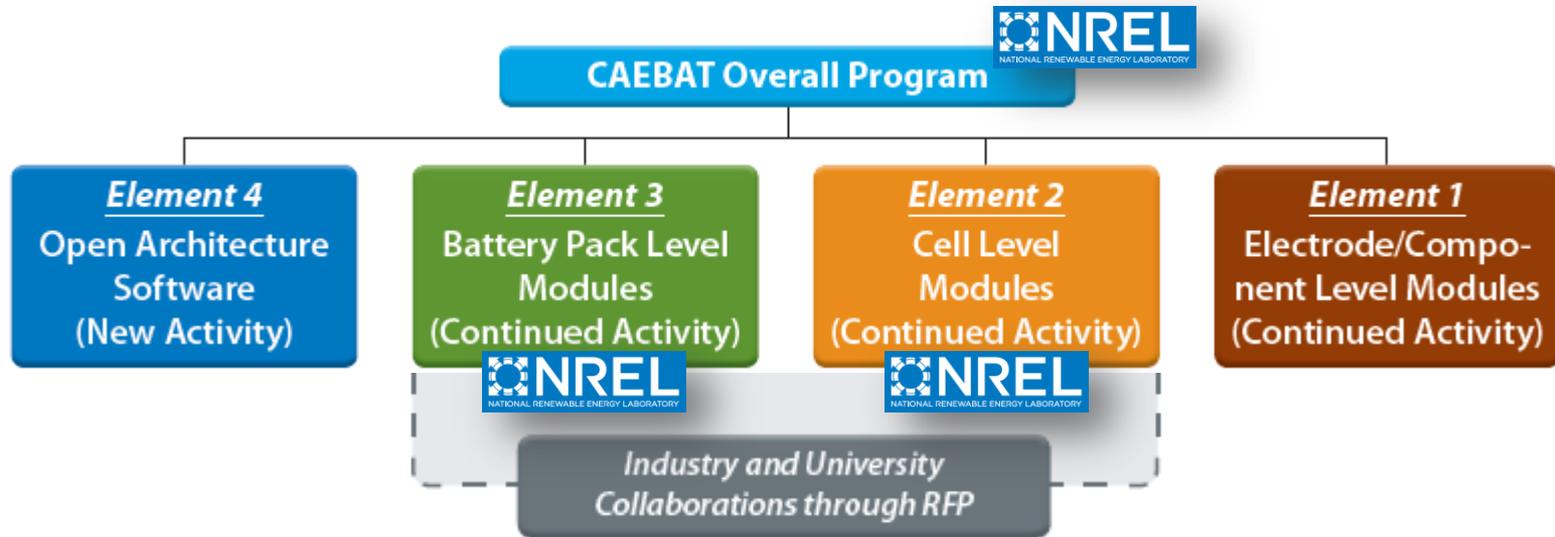
- Turn-key solution
- Commissioning within **7 days**
- Integrated in standard CTU → Ocean freight for **all climate conditions** and global use



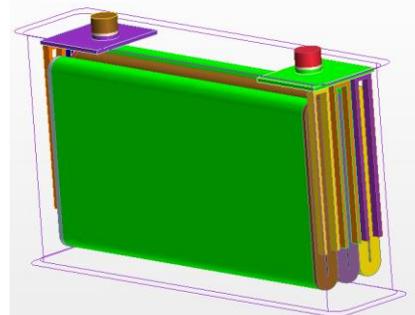
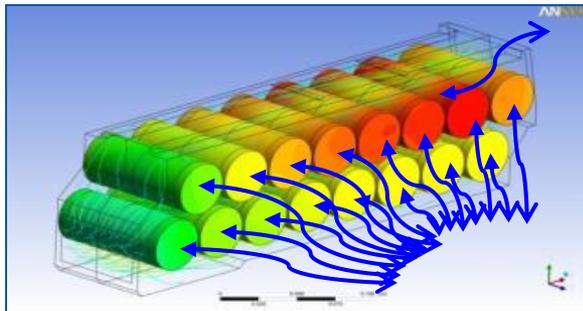
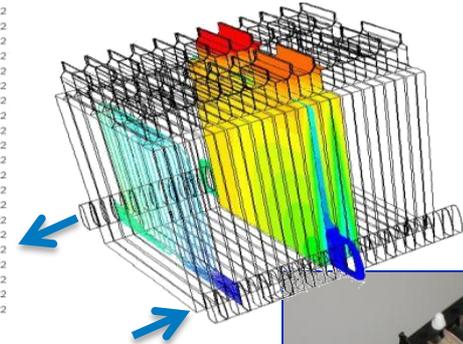
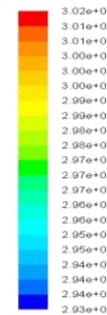
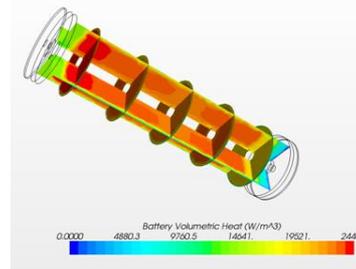
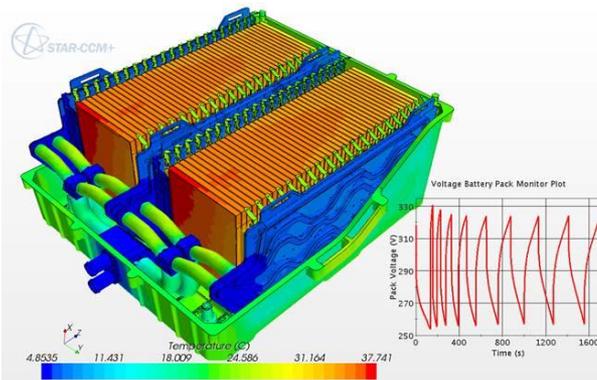
Outstanding Features

- **> 20.000 cycles** (20 years lifetime)
- **100% Depth of Discharge with no system damage**
- **< 1% self-discharge / year** (cold-standby)

- DOE VTO has established the **Computer Aided Engineering of Batteries (CAEBAT)** activity to develop “experimentally validated” software design tools to accelerate battery product development time and reduce cost
- NREL is leading a 3-year, \$20 Million, 60-40 cost shared project with industry to develop the first generation of CAEBAT tools

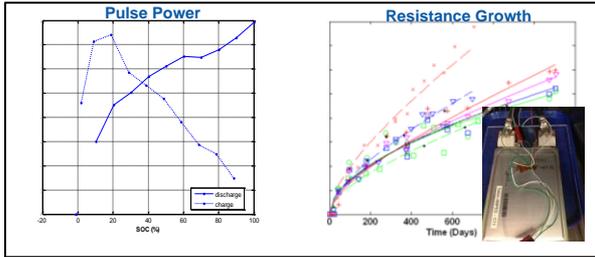


- CAEBAT developers (GM, CD-adapco, EC Power) have released beta versions of their battery design software to select end users
 - EC Power's AutoLion™ made available in December 2012
 - CD-adapco's tool for wound spiral cells in STAR-CCM+ made available in March 2013
 - ANSYS releasing Total Battery Simulator in FLUENT in August 2013
- Ford, A123, JCI, and a number of other companies are evaluating CAEBAT tools



1) Cell life test data

- Constant temperature & duty cycle

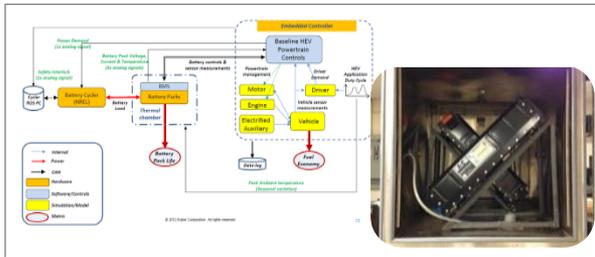


Example ARPA-E AMPED project with Eaton Corporation seeking to downsize HEV battery pack by 30-50%

2) Regress life model parameters

3) Pack life test data

- Variable temperature & duty cycle



NREL Battery Life Model

Calendar fade

- SEI growth (partially suppressed by cycling)
- Loss of cyclable lithium
- $a_1, b_1 = f(\Delta DOD, C_{rate}, T, \dots)$

Cycling fade

- active material structure degradation and mechanical fracture
- $a_2, c_2 = f(\Delta DOD, C_{rate}, T, \dots)$

$$\text{Relative Resistance } R = a_1 t^{1/2} + a_2 N$$

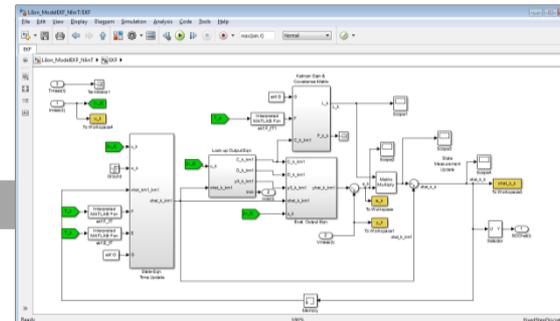
$$\text{Relative Capacity } Q = \min(Q_{Li}, Q_{sites})$$

$$Q_{Li} = b_0 + b_1 t^{1/2} + b_2 N$$

$$Q_{sites} = c_0 + c_2 N$$

4) Validated pack life model
- Forward looking prognosis based on observed I, V, T, SOC, ...

5) Control strategy prototyping



6) Closed-loop HIL testing

- NREL is working with USABC and other industry partners to develop battery thermal management
 - Supporting Denso North America to develop a low-cost and compact stand-alone battery thermal management system for electric drive vehicles
 - Supporting Gentherm to develop a high-performance, thermoelectric-based cooling system for cooling of batteries in sealed environments
- Under the ARPA-E AMPED program, we are working with three teams to develop electrical management system to optimize utilization of batteries while increasing their cycle and calendar life expectancy
 - Washington University, St. Louis: optimal operation and management of energy storage systems based on real-time predictive modeling and adaptive battery management techniques
 - Eaton: development and evaluation of predictive battery management systems for commercial hybrid vehicles
 - Utah State University: development and evaluation of robust cell-level modeling and control of large battery packs



DENSO



EATON



- NREL developed a **Battery Ownership Model**, an advanced techno-economic analysis tool
- It evaluates cost-effective pathways and business strategies to increase market adoption of energy storage and electric vehicles
- NREL found that service providers offering **battery swapping** could improve BEV economics for some drivers, but the size of the market is unknown
- NREL and partners found that **battery second use** won't be a "game-changer" for EVs, but could be a solution to automotive end-of-life battery management if sufficiently large and willing secondary markets evolve

