Overview and Progress of the Battery Testing, Design, and Analysis Activity

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Energy Storage R&D
Hybrid and Electric Systems Team
Vehicle Technologies Program

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CHARTER: Develop battery technology that will enable large market penetration of electric drive vehicles

- By 2014, develop a PHEV battery that can deliver a 40-mile all-electric range and costs $3,400
- By 2020, develop an EV battery that can store 40 kWh of electricity and costs $5,000

Energy Storage R&D FY12 $93 M

Exploratory Technology Research $22 M

Applied Battery Research for Transportation $18 M

Battery Development $42 M

Battery Testing, Design & Analysis $11 M

New Materials R&D, Diagnostics, Modeling

Next Generation Cell R&D

Battery Development & Cost Reduction

Standardized Testing Life/Cost Projections Design Tools
Testing (~60% of TDA funding)

Core Testing Facilities

- Technology Life Verification Testing
- Smart Battery Status Monitor
- Developmental and Applied Diagnostics

Developmental Test Methods and Tools

- Development of Techniques to Study Internal Shorts
- Internal Short Circuit Emulation
- Aged Cell Testing

Performance

- INL

Thermal

- NREL

Abuse

- Sandia National Laboratories
Battery Performance Testing

- **Battery Testing Protocols and Targets**
  - Develop battery performance and cycle life test protocols based on different EDV architectures
  - Assist in development of battery system targets

- **Current Test Procedures (posted at http://www.uscar.org)**
  - FreedomCAR Battery Test Manual for Plug-in HEV
  - FreedomCAR Power Assist Battery Test Manual
  - Electric Vehicle Battery Test Procedures Manual
  - FreedomCAR 42 Volt Battery Test Manual
  - FreedomCAR Ultracapacitor Test Manual
  - Battery Technology Life Verification Test Manual
  - Energy Storage Abuse Test Manual for HEV Applications
  - USABC Abuse Test Procedures Manual (EVs)

Many have been globally adopted: the abuse test manuals are the basis for SAE standards.

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Collaboration on International Battery Testing Protocols

- Battery testing is a time-consuming and costly process
- Parallel testing efforts, such as those in the U.S., China, Europe, Japan, and South Korea, may be better leveraged through international collaboration
- The collaboration may establish standardized, accelerated testing procedures and data analysis methods, which may accelerate electric vehicle development and deployment
- Partners in the collaboration: U.S., China, Italy, Austria, S. Korea, and Sweden
- There are three steps in the collaborative effort
  - Collect and discuss battery test protocols from various organizations/countries
    - The battery test protocols from the US, Europe and Japan were collected and compared. The initial comparison showed differences in testing assumptions, approach and philosophy
  - Conduct side-by-side tests on small cells using all protocols for a given application, such as an EV, to determine differences in stress levels and data quality
  - Compare the results, noting similarities and differences between protocols and test sites

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Life Validation Testing

- The Battery Technology Life Verification Test (TLVT) and Battery Life Estimator (BLE) Manuals are designed to predict battery life within a short period of accelerated aging.

- The software is based on statistically robust fitting methods using both linear and non-linear approaches.

- Memory effect studies using Sanyo cells are underway.
  - Results will improve modeling and fitting capabilities (linear and non-linear) in the software package.

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**Battery Life Data Analysis Software**

**Curve Fitting and Life Projection**

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Need/Objective

- **Need:** Long-term use of lithium-ion batteries in vehicles represents a significant warranty commitment. But there is insufficient knowledge of their aging processes, in particular of the strong path dependence of their performance degradation.

- **Objective:** Establish a platform of developmental and applied diagnostic testing to examine mechanistic contributions to cell aging, develop complementary advanced modeling tools, and optimize operational protocols to minimize the aging process.

Key Targets

- Aging due to **temperature** variation
- Charge limitations; **self-discharging** behavior
- Contributions to **capacity loss**
- Cell behavior over **thermal regime**
- Optimization of Pouch Cell **Pressure** to increase performance/life
- Prolonging cell life by **current “conditioning”**
- Prolonging cell life by optimization of **usage patterns**

**Lithium-ion Chemistry: Sanyo ‘Y’ Cells**

- Configuration: 18650
- Cathode: \{LiMn_2O_4 + LiMn_{1/2}Ni_{1/2}Co_{1/2}O_2\}
- Anode: graphitic
- \( V_{\text{max}} = 4.2 \text{ V (100\% SOC)} \)
- \( V_{\text{min}} = 2.7 \text{ V (0\% SOC)} \)
- \( C_{1/1} \) discharge capacity: 1.86 Ah
Laboratory impedance measurements require costly equipment (~$50,000) and typically take more than an hour to complete.

The Impedance Measurement Box (IMB) enables rapid impedance measurements over a broad frequency range:
- Measures impedance in about 10s and uses low-cost hardware (~$50) that can be embedded in the battery while in the vehicle.

Rapid impedance measurements provide a new diagnostic tool for more accurate onboard battery state-of-health assessment.

The IMB was awarded an R&D100 Award in 2011.

The IMB development is based on a collaborative effort between a national laboratory, university, and small business.

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Safety & Abuse Testing of Batteries is of Central Importance

- Safety, along with cost and life, is a key barrier to introduction of advanced, high energy rechargeable batteries into vehicles
  - The safety of large cells and large capacity batteries, such as used for vehicle traction, is more difficult to manage than small cells and batteries
  - Vehicle environment is challenging (temperature, vibration, etc.)

- Safety is a systems issue, with many inputs and factors
  - “Safe” cells and batteries can be unsafe in applications because of poor engineering implementation or incomplete understanding of system interactions

- Standardized tests are crucial to obtain a fair comparison of different technologies and to gauge improvements
  - Outcome of safety and abuse tolerance tests strongly influenced by experimental conditions.
  - Standardized tests can remove most to the variability

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Safety/Abuse Tolerance Testing (Cont’d)

- **Li-ion Safety Issues**
  - High energy density
  - Reactive materials
  - Flammable electrolytes

- **Abusive Conditions**
  - Mechanical (crush, penetration, shock)
  - Electrical (short circuit, overcharge, over discharge)
  - Thermal (over temperature from external or internal sources)

- **Abuse Testing Methodology**
  - SAE Abuse Test Manual J2464

- **Typical Tests**
  - 1 & 10 mohm short circuit
  - 1C & 32A Overcharge/Overdischarge
  - Thermal Ramp @ 100% SOC & 90%SOC
  - Mechanical crush on both the positive and negative sides @ 100% SOC
  - Nail penetration @ 100% SOC

Unacceptable

Preferable
Design and Analysis (~40%)

Computer Aided Engineering for Batteries (CAEBAT)

- 3 Industry Awards
  - CD-adapco
  - EC-Power
  - GM
- Multi-Scale Multi-Dimensional Modeling
- Abuse Reaction and Thermal Runaway Modeling

CAEBAT Overall Program

Component Level Models

Cell Level Models

Battery Pack Level Models

Open Architecture Software

Battery Secondary Use Study

Battery Ownership Modeling

Battery Life Trade-Off Studies

• NREL
• Center for Sustainable Energy California
• UC San Diego
• SDGE
• UCDavis
Relevance – Need for CAEBAT

- Computer-Aided Engineering (CAE) tools are widely used in many industries to speed up the product development cycle and reduce the number of trial and error attempts.
- CAE tools have enabled automakers to reduce product development cost and time while improving safety, comfort, and durability of vehicles and their components.
- Although DOE has provided past funding for modeling efforts, they either
  - Included relevant physics details, but neglected engineering complexities, or
  - Included relevant macroscopic geometries and system conditions, but used too many simplifications in fundamental physics.
- No mature CAE tools exist for the design and development of electric drive vehicle batteries.
Physics of Li-ion Battery System in Different Length-Scales

Scale of Electrodes
- Charge balance and transport
- Electrical network in composite electrodes
- Li transport in electrolyte phase

Scale of Cells
- Electronic potential & current distribution
- Heat generation and transfer
- Electrolyte wetting
- Pressure distribution

Scale of Particles
- Li diffusion in solid phase
- Interface physics
- Particle deformation & fatigue
- Structural stability

Scale of Modules
- Thermal/electrical inter-cell configuration
- Thermal management
- Safety control

Scale of System
- System operating conditions
- Environmental conditions
- Control strategy

Scale of System
- Environment conditions
- Control strategy

Active Research

Present Industry Needs
program is intended to incorporate existing and new models into a battery design suite with the goal of shortening battery design cycles and optimizing batteries (cells and packs) for improved performance, safety, long life, and low cost.

- Battery design suite must address multi-scale physics interactions, be flexible, expandable, validated and verified.
Industry Collaboration

- Solicitation issued for industry to address Elements 2 & 3
- 3 teams were selected:
  - EC Power / PSU / Ford / JCI
  - CD-adapco / Battery Design / A123 / JCS
  - GM / ANSYS / E-Sim

- Projects started Summer 2011
  - Completed first version release of cell level software
  - Started cell level testing and validation
CAEBAT Final Goal

- ANSYS Pack Model (Fluent)
- NREL Cell Model (Matlab)
- ANL Electrode Model (Excel)
- LBL Electrode Model (Fortran)
- CD-adapco Pack Model (CCM+)
- BDS Cell Model (C++)

Model input/output
Standard information
Interface/translator
Standard input/output
Multi-scale Model Framework for Better Li-Ion Battery Design

**Summary**
- Ground-breaking methodology for multi-domain modeling of lithium-ion batteries encompassing multi-physics in varied length scales.

**Approach**
- Developed a multi-domain modeling approach known as the Multi-Scale Multi-Dimensional (MSMD) framework for predictive computer simulation and design of lithium-ion batteries (LIBs) with different chemistries or geometries.
- Introduces multiple computational domains for corresponding length scale physics, and decouples geometries between submodel domains while coupling physics bi-directionally.
- Through the Computer-Aided Engineering for Electric Drive Vehicle Batteries (CAEBAT) program, NREL is sharing know-how with the three award contractor teams.

The MSMD framework resolves intricate LIB geometries into multiple computational domains for corresponding length scale physics.

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Battery Ownership Model (BOM)

- Many new vehicle technologies, power sources, infrastructure technologies, and business models proposed for transportation
- The main goal is to assist in understanding how various business plans for electric vehicles compare to other technologies
- Present studies
  - EV Cost Sensitivities
  - Service provider / Battery Swapping
  - Niche Markets
  - Electric Drive Platform Performance Targets
  - Charging Strategies
  - Secondary Use
  - Fast Charging

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Issue a request for proposals to expand upon the current state of electric drive vehicular battery computer-aided engineering models. Specific areas of interest include but are not limited to:

- Improving the computational efficiency of current models
- Developing models capable of predicting the coupled structural, electrical, and thermal responses to abusive conditions
- Developing advanced life prediction modeling
- Developing models focused on predicting degradation and failure mechanisms

Funding and Period of Performance

- Total DOE and TARDEC funding for this solicitation: $1.5M to $3M/year
- Expected number of awards: 3-6
- Length of each project: 1-3 years
- Industry cost share: 50% of industry effort (cost-sharing is waived for university and national lab participants)
TDA is an important portion of the energy storage portfolio that provides valuable feedback on programmatic performance goals and highlights potential gaps and opportunities.

Test methods and modeling activities are under development to understand the safety and degradation mechanisms associated with energy storage technologies.

Besides our core facilities many activities are transitioning to a competitively awarded process.