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

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Tuesday, May 14, 2013

Project ID: ES116

Battery R&D Budget

Battery/Energy Storage R&D Funding ($, M)	
FY 2012* Enacted	$90
FY 2013 Full Year CR**	$88
FY 2014* (request)**	$170.5

*FY 2012 SBIR/STTR removed.
**FY 2013 full year CR inclusive of SBIR/STTR.
*** FY 2014 budget request inclusive of SBIR/STTR.

FY 2013 Energy Storage R&D Budget** ($88M)

Energy Storage R&D

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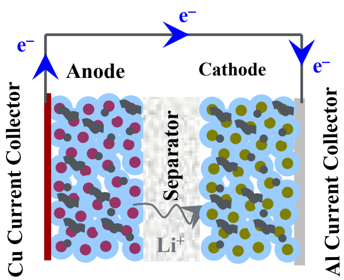
CHARTER: Develop battery technology that will enable large market penetration of electric drive vehicles

- By *2014*, develop a PHEV battery that can deliver a 40-mile all-electric range and costs $3,400
- By *2022*, develop an EV battery that can store 40 kWh of electricity and costs $5,000

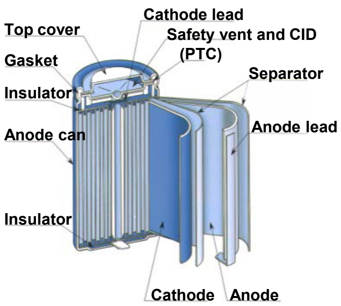
Energy Storage R&D

Exploratory Technology Research



New Materials R&D, Diagnostics, Modeling

Applied Battery Research for Transportation



Next Generation Cell R&D

Battery Development

Battery Development & Cost Reduction

Battery Testing, Design & Analysis

Standardized Testing Life/Cost Projections Design Tools

Testing (~60% of TDA funding)

	Performance	Thermal	Abuse
Core Testing Facilities for Deliverables	INL; Argonne National Laboratory	NREL National Renewable Energy Laboratory	Sandia National Laboratories
Developmental Test Methods and Tools	• Technology Life Verification Testing • Smart Battery Status Monitor • Developmental and Applied Diagnostics		• Development of Techniques to Study Internal Shorts • Internal Short Circuit Emulation • Aged Cell Testing

Battery Testing Throughput

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Performance

INL

Over 20 programs tested

- > 350 cells
- > 50 modules
- 1 pack

Argonne NATIONAL LABORATORY

Over 15 programs tested

- > 200 cells
- > 8 modules
- 2 packs

Abuse

Sandia National Laboratories

Over 10 programs tested

- > 200 cells
- > 10 modules

Thermal

NREL NATIONAL RENEWABLE ENERGY LABORATORY

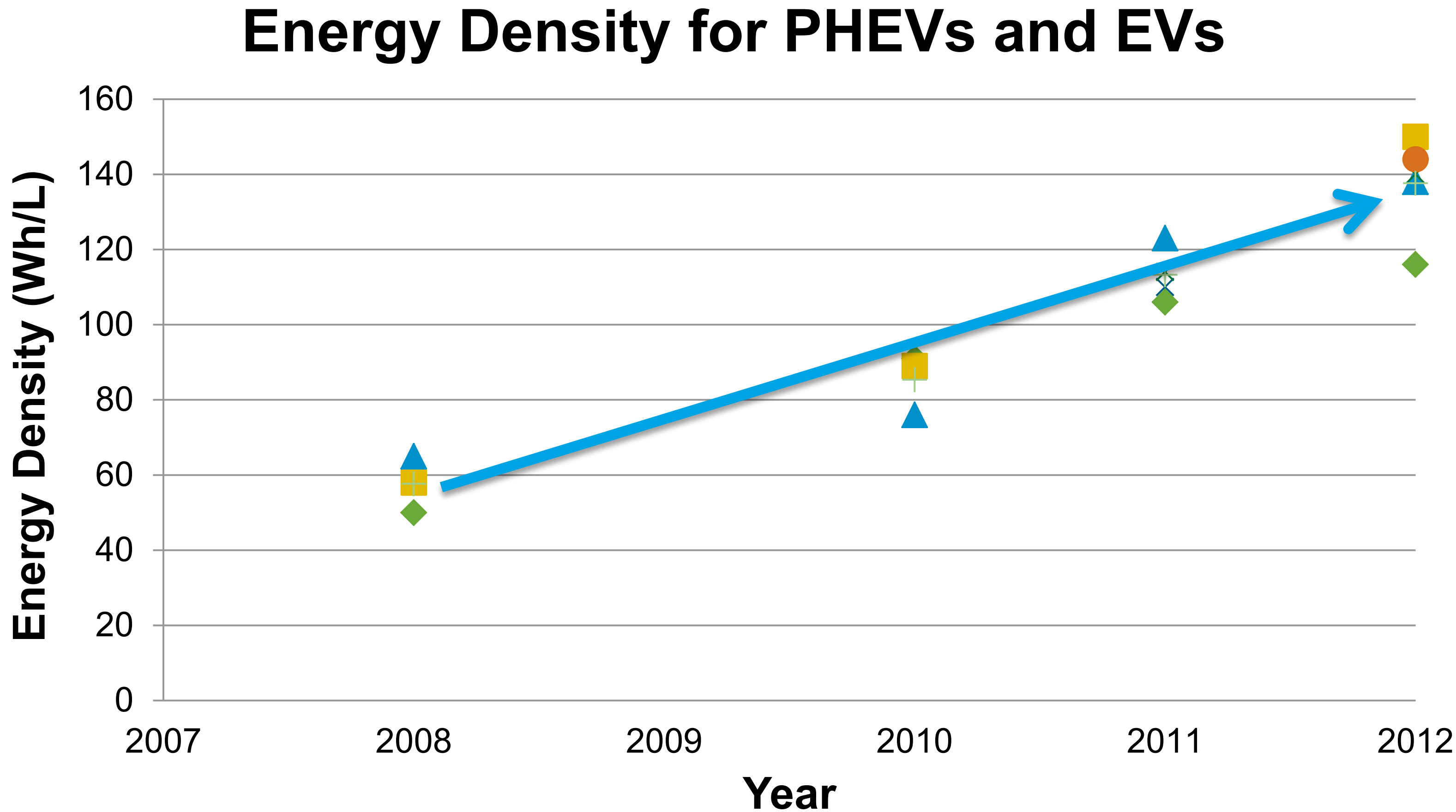
Over 10 programs tested

- > 40 cells
- > 2 modules
- 2 packs

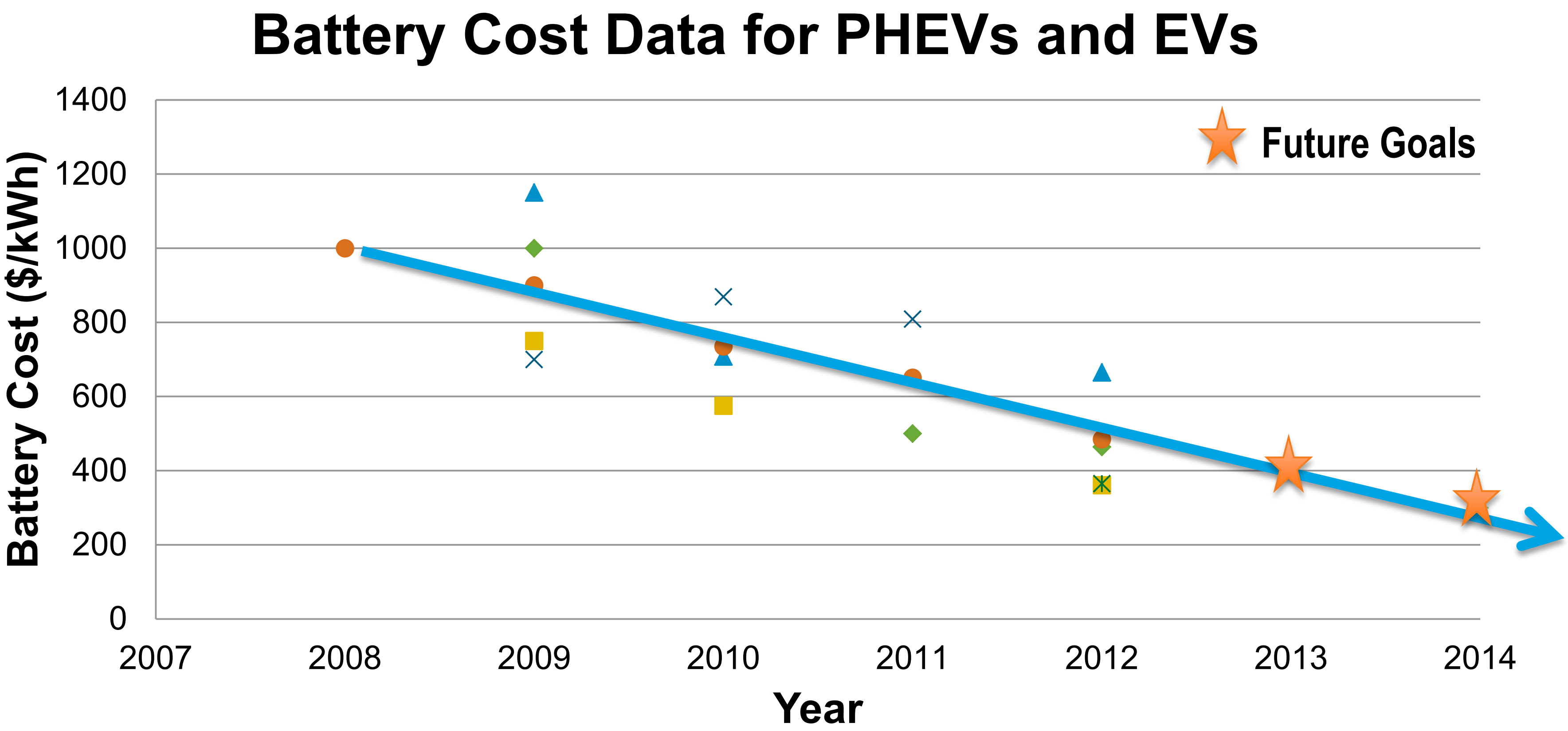
Battery Programs Tested

Johnson Controls
SK energy
DOW KOKAM
COBASYS
SAMSUNG
3M
ActaCell
international battery
INVENTEK CORPORATION
LISHEN
A123 SYSTEMS
cpi compact power, inc.
LG Chem
envia SYSTEMS
AXION POWER INTERNATIONAL INC.
QUALLION
K2 Energy
Maxwell TECHNOLOGIES
Leyden energy
saft
Hydro Québec
ENTEK INTERNATIONAL
MILTEC
amprius
APPLIED MATERIALS
nanosys
SAKTI3
SEEO
FARASIS
EXIDE BATTERIES
EAST PENN manufacturing co., inc.

Battery Testing Trends



As DOE expanded its focus from HEVs to PHEVs in 2008, energy density of system deliverables at end-of-life has increased from about 60 Wh/L to just over 140 Wh/L. DOE's goal for 2022 is 400 Wh/L.



As DOE expanded its focus from HEVs to PHEVs in 2008, the cost of useable energy at the system level of program deliverables has decreased from about $1000/kWh to just under $500/kWh. DOE's goal in 2022 is $125/kWh.

Battery Performance Testing

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- **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**

The EV Goals are currently under review

- **Current Test Procedures (posted at http://www.uscar.org)**
  - **Battery Test Manual for Plug-in HEV (PHEV)**
  - **Power Assist Battery Test Manual (HEV)**
  - **Electric Vehicle Battery Test Procedures Manual (EV)**
  - ★ **Test Manual for Low-Energy Storage System (LEESS) for HEVs**
  - ★ **Battery Test Manual for 12-Volt Start Stop System**
  - **42 Volt Battery Test Manual**
  - **Ultracapacitor Test Manual**
  - ★ **Battery Technology Life Verification Test Manual**
  - **Energy Storage Abuse Test Manual for HEV Applications**
  - **Abuse Test Procedures Manual (EVs)**

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

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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 of 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

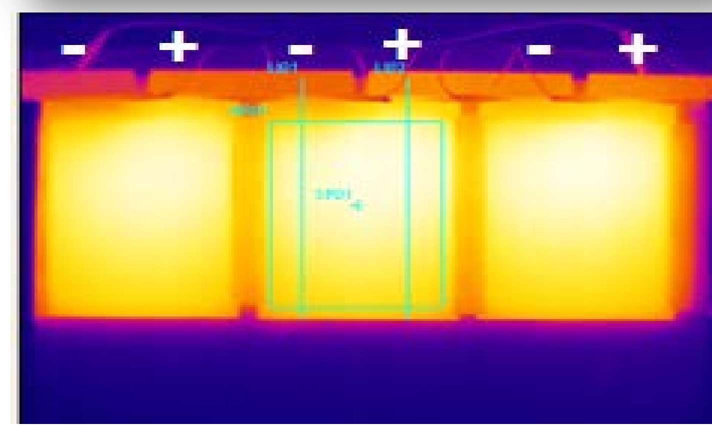
Cell/Module/Pack Thermal Testing

Objectives/Results

- **Thermally characterized cell and battery hardware** and provided technical assistance and **modeling support to DOE/USABC battery** developers for improved designs

- Enhanced and validated **physics-based models** to support the design of long-life, low-cost energy storage systems

- Quantified the **impact of temperature and duty-cycle** on energy storage system **life and cost**



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Design and Analysis

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

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Center for Sustainable Energy CALIFORNIA

SDG&E connected

UC DAVIS

UC San Diego Local Impact, National Influence, Global Reach

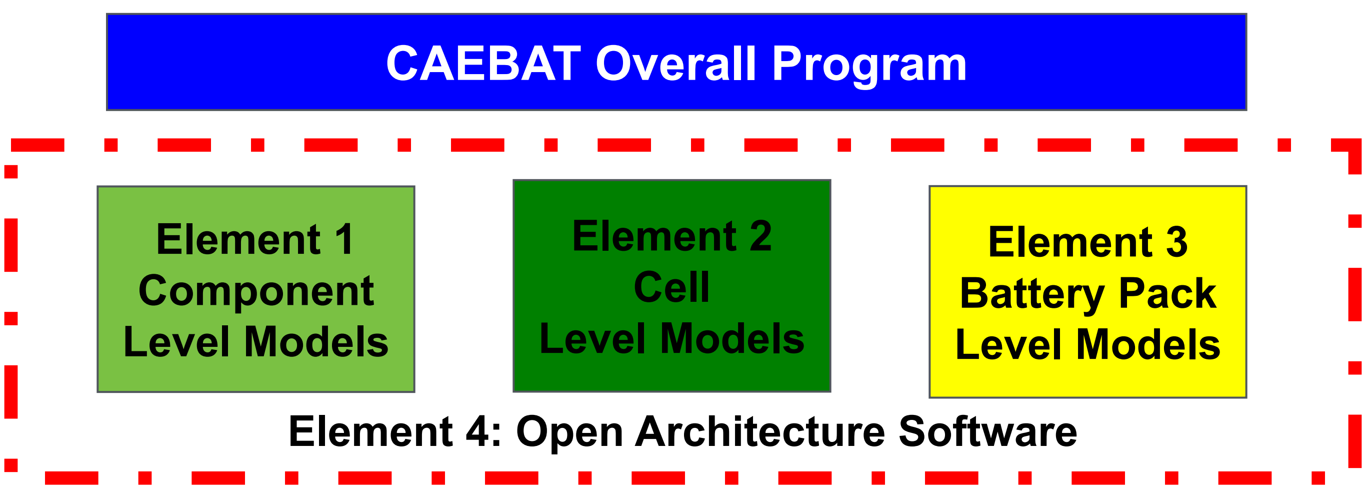
AV aerovironment

Battery Ownership Modeling

Battery Life Trade-Off Studies

CAEBAT Objectives

- 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 Highlights

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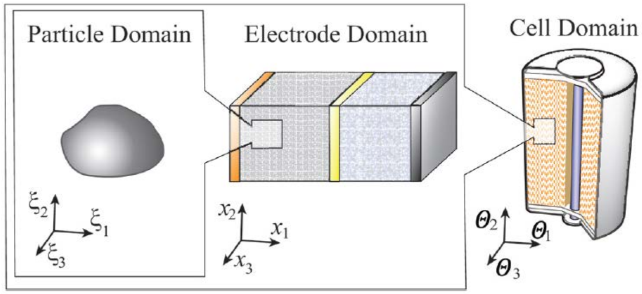
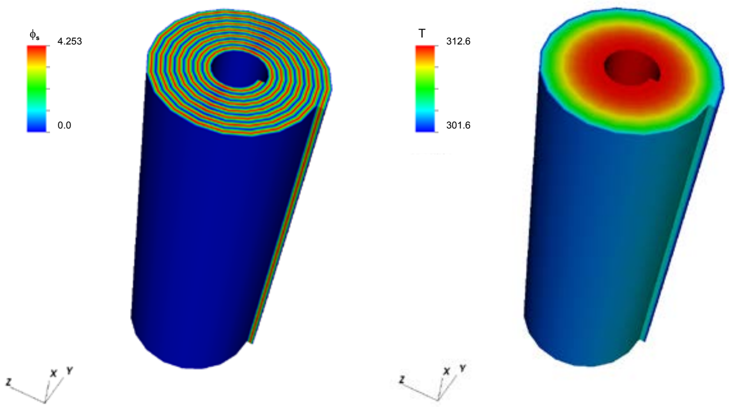
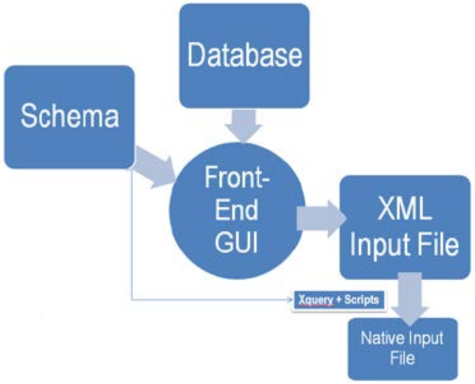
- NREL successfully transferred their MSMD framework to industry partners
- All three industry partners have completed and released beta versions of their cell code within their teams or to the public
- ORNL has developed the first version of input standards for the Battery State and started to create translators for industry partners that successfully link industry models to the open architecture







CAEBAT Highlights

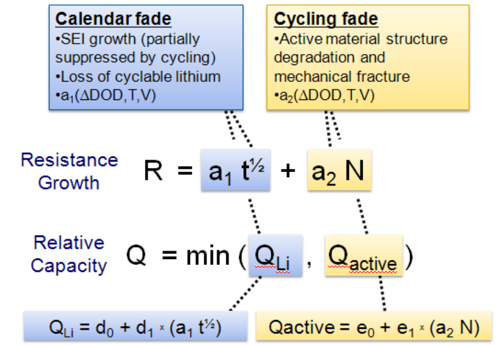
- Industry partner successfully incorporated electrolyte properties that were developed in a previous project funded by DOE out of INL
- Software developed in CAEBAT have been used to simulate battery performance by Nissan, FMC, GM, Opel, Ford, Hitachi Maxell, Hyundai Mobis, and Carnegie Mellon University
- The SAE committee on battery testing will develop guidelines on battery testing specifically for modeling as a direct outgrowth of some of the challenges and lessons learned from the CAEBAT program

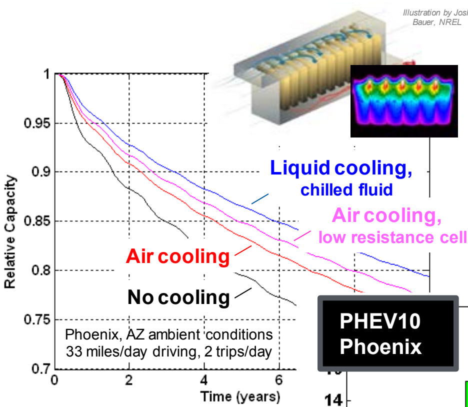
Current Solicitation: CAEBAT II

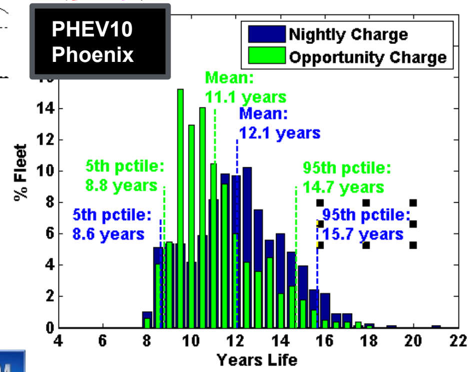
- Issued a request for proposals to expand upon the current state of electric drive vehicular battery computer-aided engineering models
- Specific areas of interest include but are not limited to:
  - Improving the computational efficiency of current models
  - Developing models capable of predicting 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)

Battery Life Tradeoff Studies

- **Objectives**
  - **Quantify tradeoffs in battery life with duty-cycle and environment**
  - **Identify systems/controls that maximize battery utilization & lifetime; minimize cost**
- **Approach**
  - Li-ion lifetime predictive models for techno-economic analysis based on Li-ion physics of degradation
    1. SEI growth as f(t, T,SOC,C_{rate})
    2. Active material loss as f(N, DOD,C_{rate}, …)
- **Results**
  - Leveraged private & public aging datasets for life model parameterization & validation (NCA, FeP,…)
  - Performed analyses of realistic xEV drive cycles, US climates and thermal control
  - Life model implemented in NREL Battery Ownership Model + licensed externally







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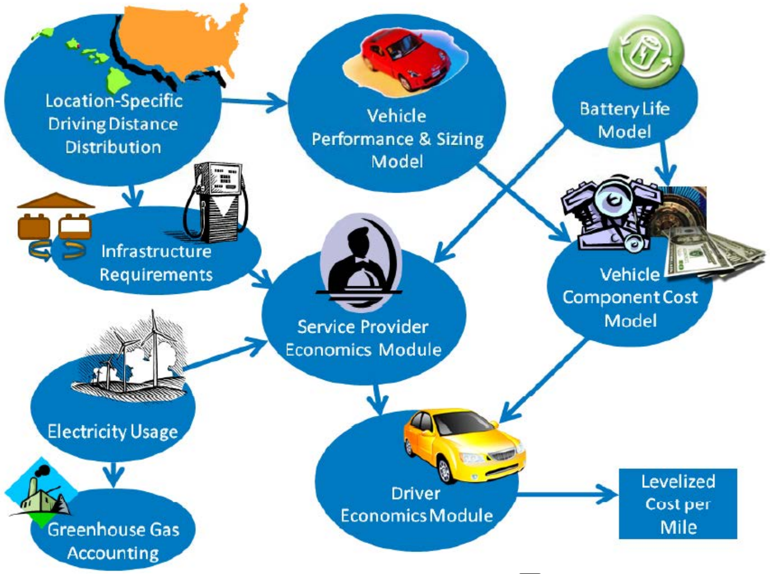
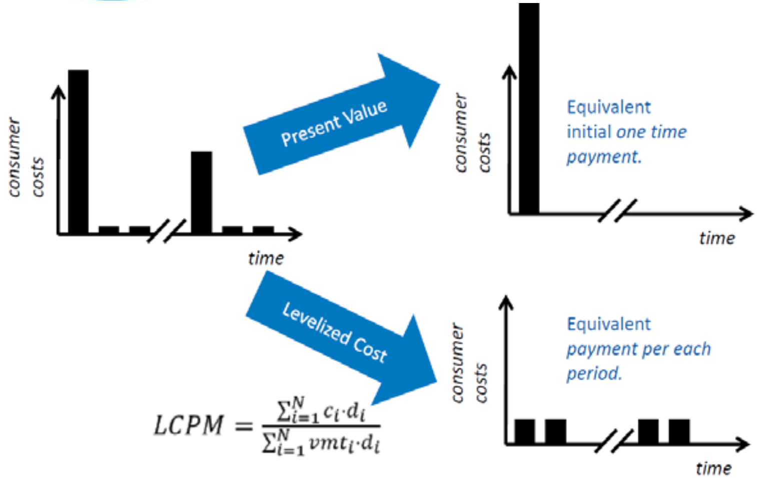
Battery Ownership Model (BOM)

- 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**





$$LCPM = \frac{\sum_{i=1}^{N} c_i \cdot d_i}{\sum_{i=1}^{N} vmt_i \cdot d_i}$$

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Summary

- 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

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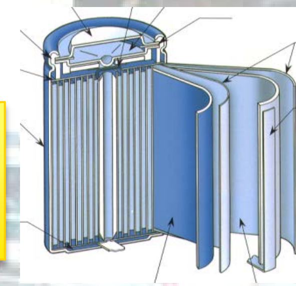

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Collaboration on International Battery Testing Protocols

- 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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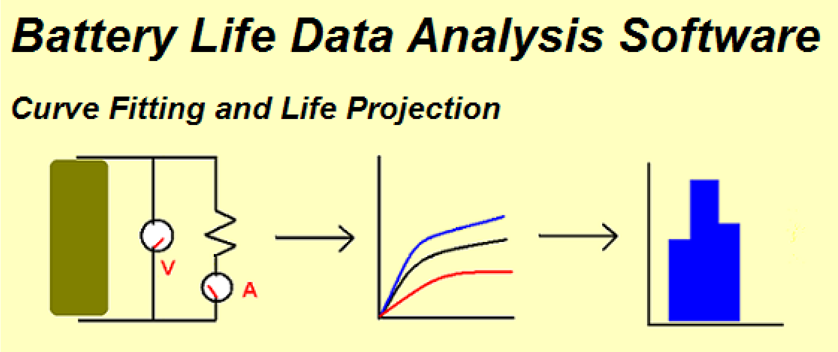
Life Validation Testing

- 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
  - Software commercially available at the Argonne Software Shop (http://www.anl.gov/techtransfer/Software_Shop/index.html).
- 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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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: $\{LiMn_2O_4 + LiMn_{1/3}Ni_{1/3}Co_{1/3}O_2\}$
Anode: graphitic
V_{max} = 4.2 V (100% SOC)
V_{min} = 2.7 V (0% SOC)
$C_1/1$ discharge capacity: 1.86 Ah

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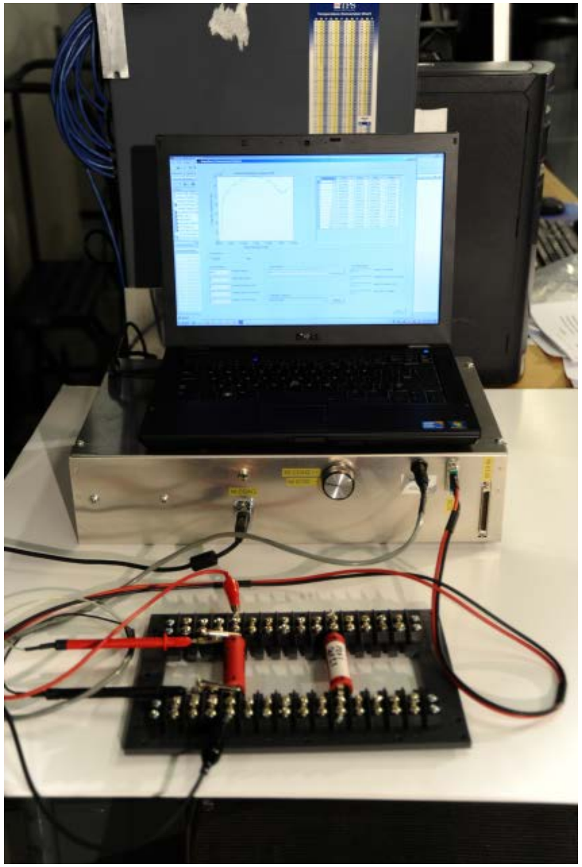
Smart Battery Status Monitor

- 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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Modeling Length Scales

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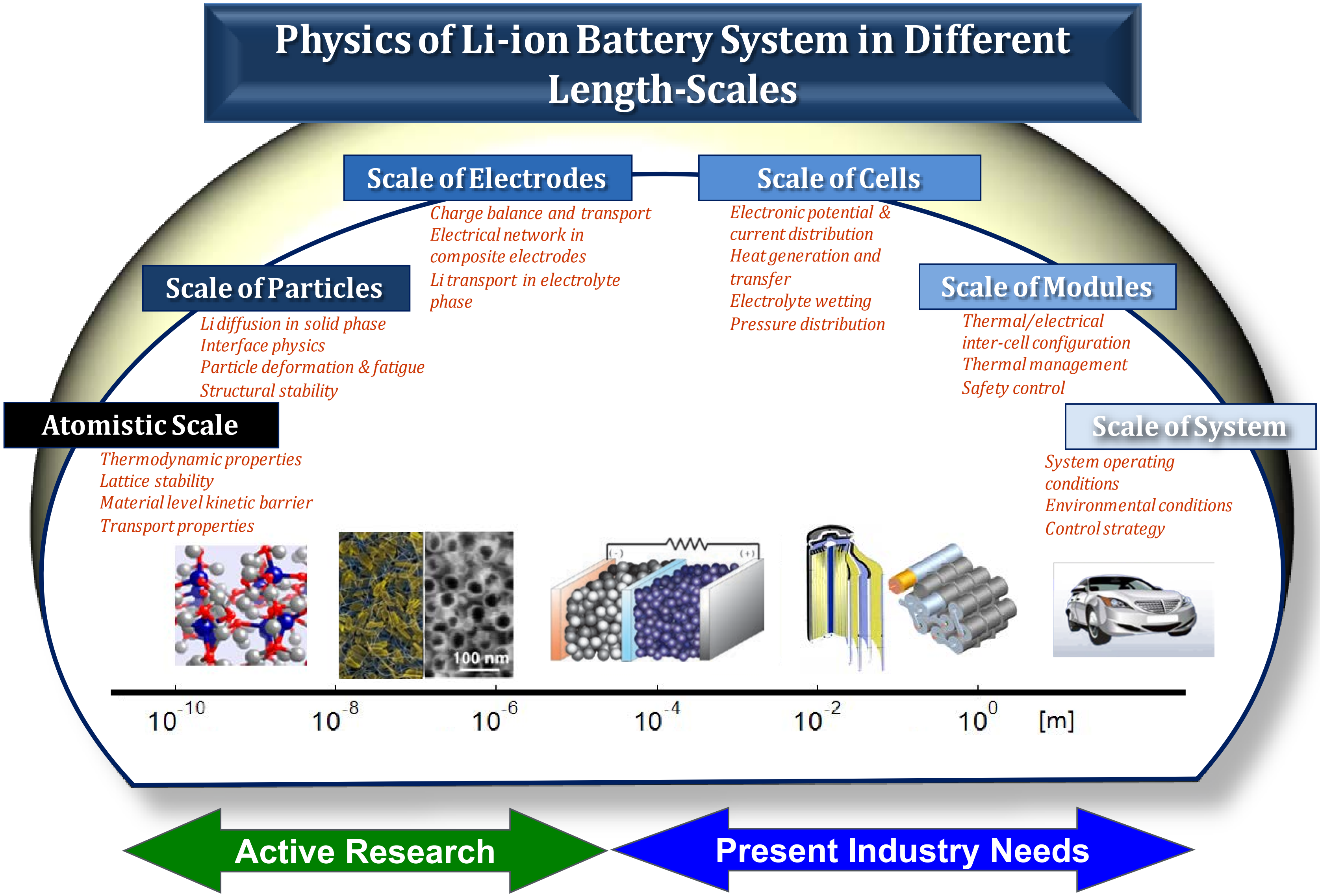
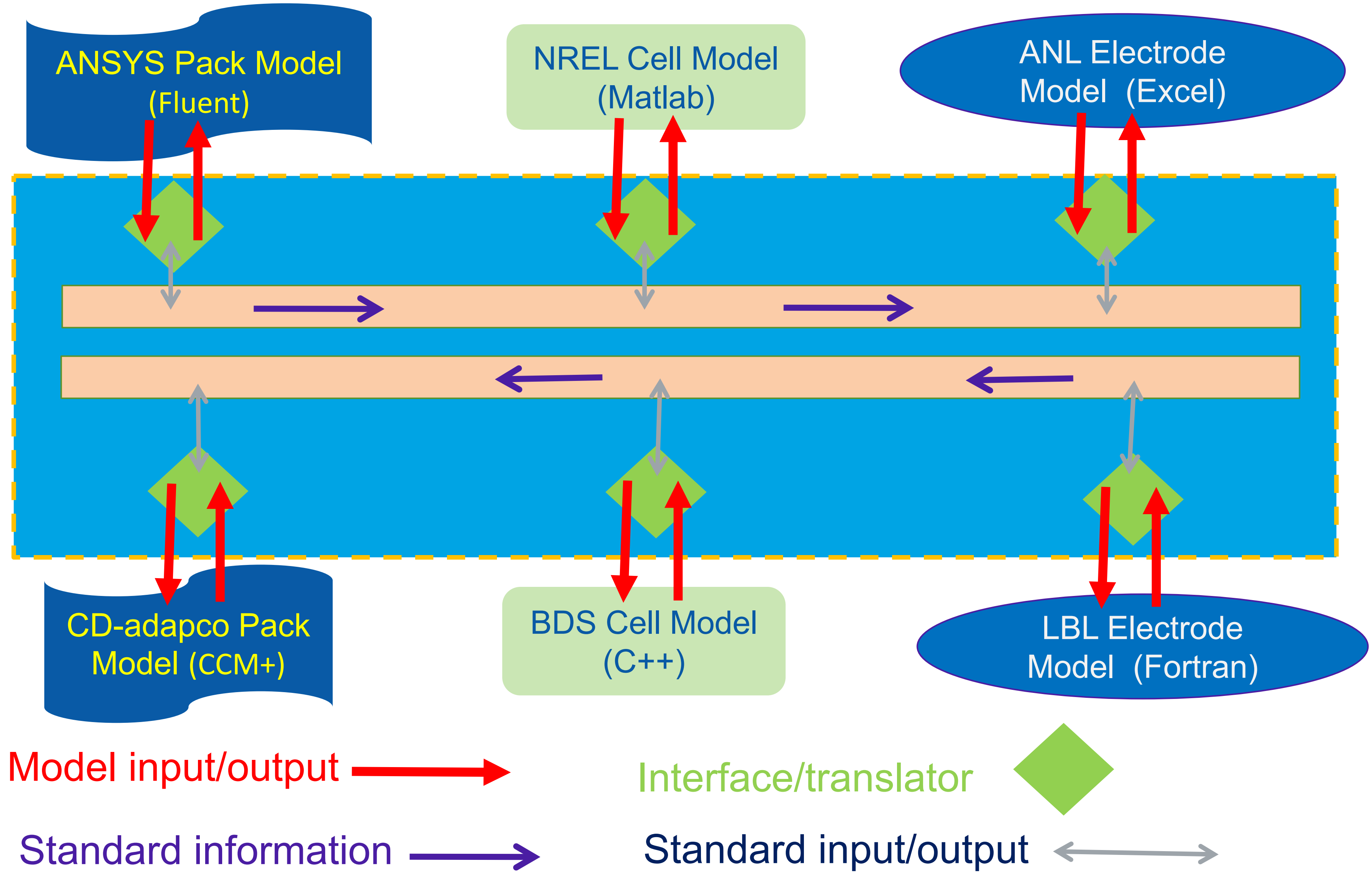


CAEBAT Final Goal



Multi-scale Model Framework for Better Li-Ion Battery Design

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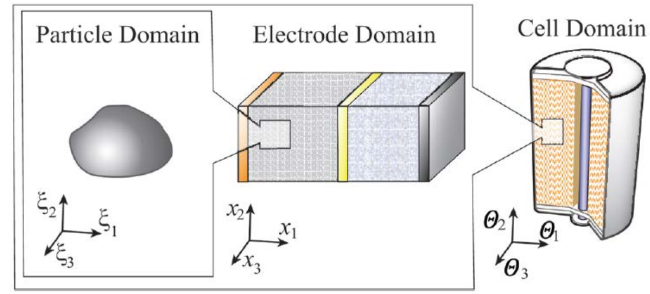
❑ Summary

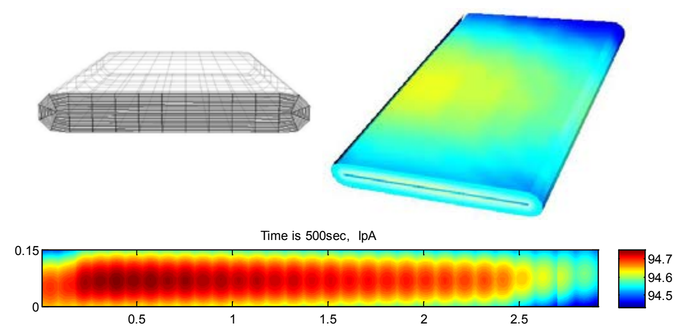
- ➢ Ground-breaking methodology for multi-domain modeling of lithium-ion batteries encompassing multi-physics in varied length scales .

❑ 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.



The MSMD application to a computational study on large format prismatic wound cell behaviors; Transfer reaction current density distribution after 500 sec at 4C discharge of 20Ah cell with continuous tab

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