Batteries for Automotive Applications

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National Nuclear Security Administration

FreedomCAR & Fuel Partnership

Hybrid Electric Vehicles
Main Emphasis of Vehicle Electrification

What Are the Advantages of HEVs?

Hybrid electric vehicles have several advantages over conventional vehicles:

- Greater operating efficiency because HEVs use regenerative braking, which helps to minimize energy loss and recover the energy used to slow down or stop a vehicle;

- Lighter engines because HEV engines can be sized to accommodate average load, not peak load, which reduces the engine's weight;

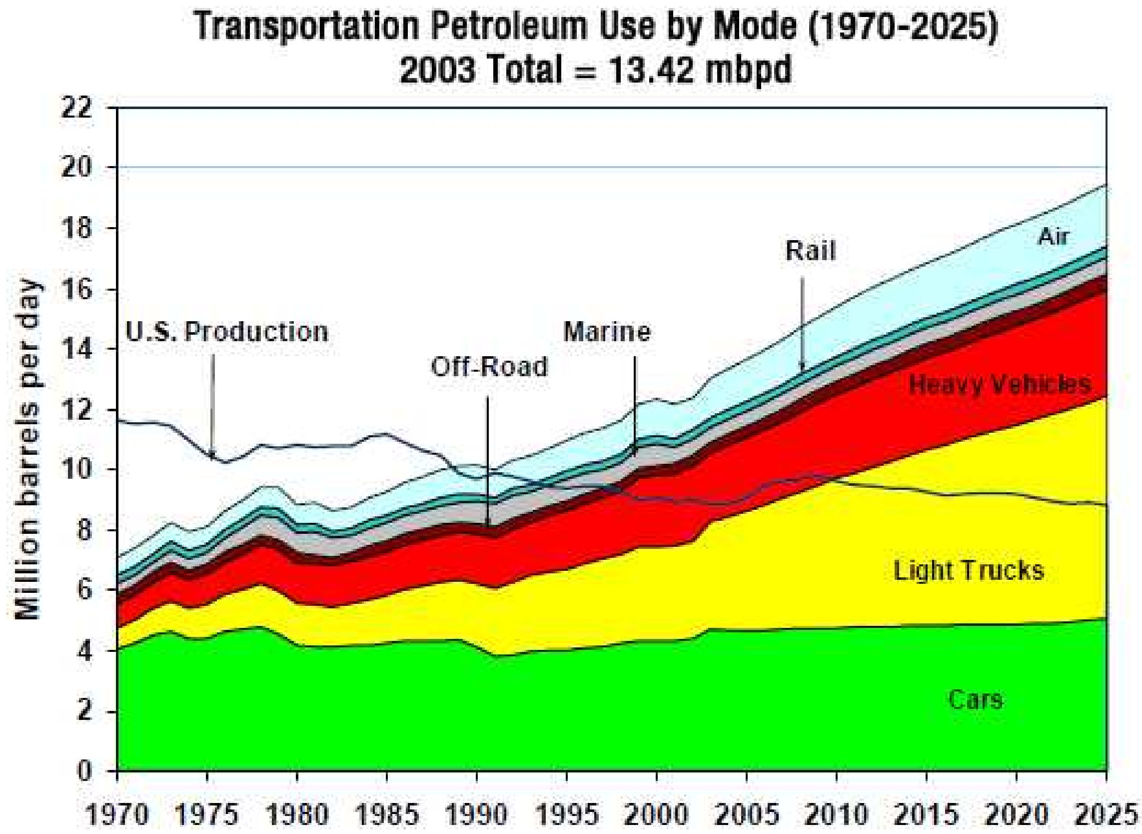
- Greater fuel efficiency because hybrids consume significantly less fuel than vehicles powered by gasoline alone;

- Cleaner operation because HEVs can run on alternative fuels (which have lower emissions), thereby decreasing our dependency on fossil fuels (which helps ensure our national security); and

- Lighter vehicle weight overall because special lightweight materials are used in their manufacture.

Historical and Projected Oil Consumption by Transportation Sector and U.S. Oil Production

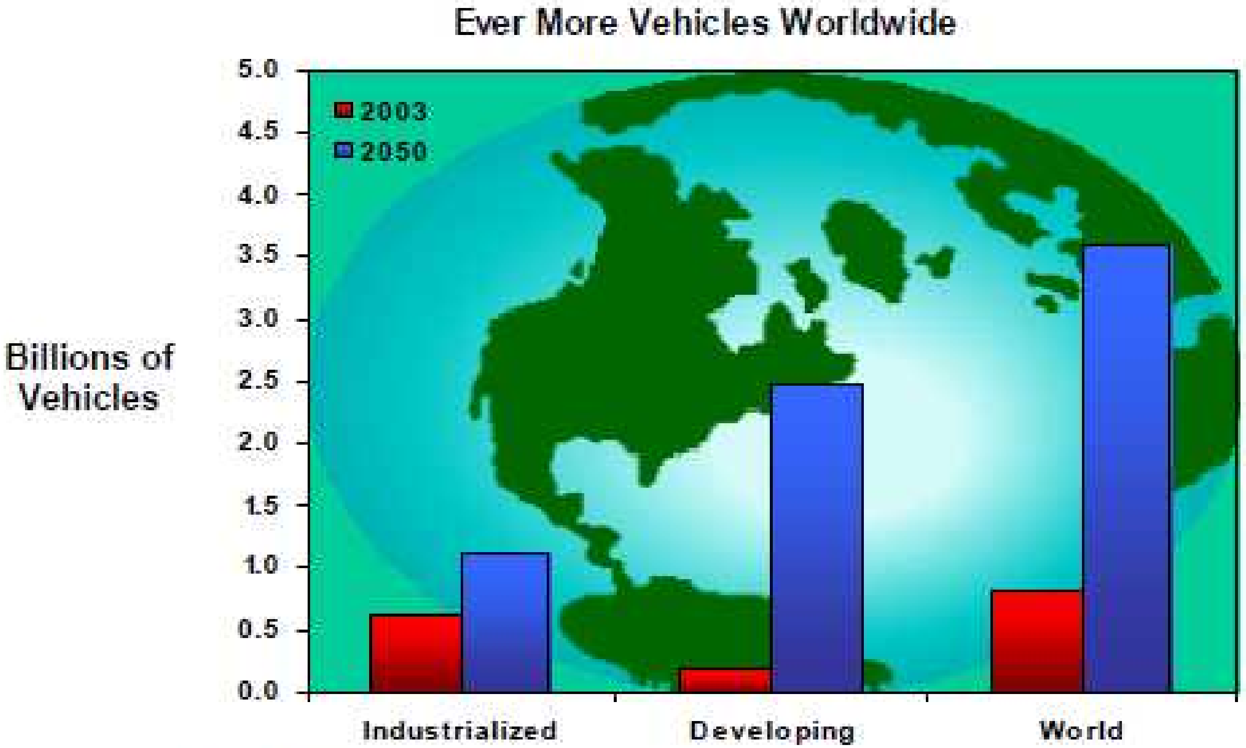
Domestic oil production has been steadily declining for over two decades, and oil imports are expected to reach 70 percent of all oil consumed in the United States by 2025.



Note: The sharp increase in values between 2003 and 2004 are caused by the data change from historical to projected values.
Source: Transportation Energy Data Book: Edition 24, ORNL-6973, December 2004, and EIA Annual Energy Outlook 2005, February 2005.

Motor Vehicle Registration Growth

Not only is the U.S. oil demand growing, but global demand in both industrialized and developing countries is increasing rapidly.



Source: EE Analytic Team

DOE FreedomCAR and Vehicle Technology Program

The Mission

The mission of the Vehicle Technologies Program is to develop more energy efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum. The long-term aim is to develop "leap frog" technologies that will provide Americans with greater freedom of mobility and energy security, with lower costs and lower impacts on the environment.

The Vision

Transportation energy security will be achieved through a U.S. highway vehicle fleet of affordable, full-function cars and trucks that are free from petroleum dependence and harmful emissions without sacrificing mobility, safety, and vehicle choice.

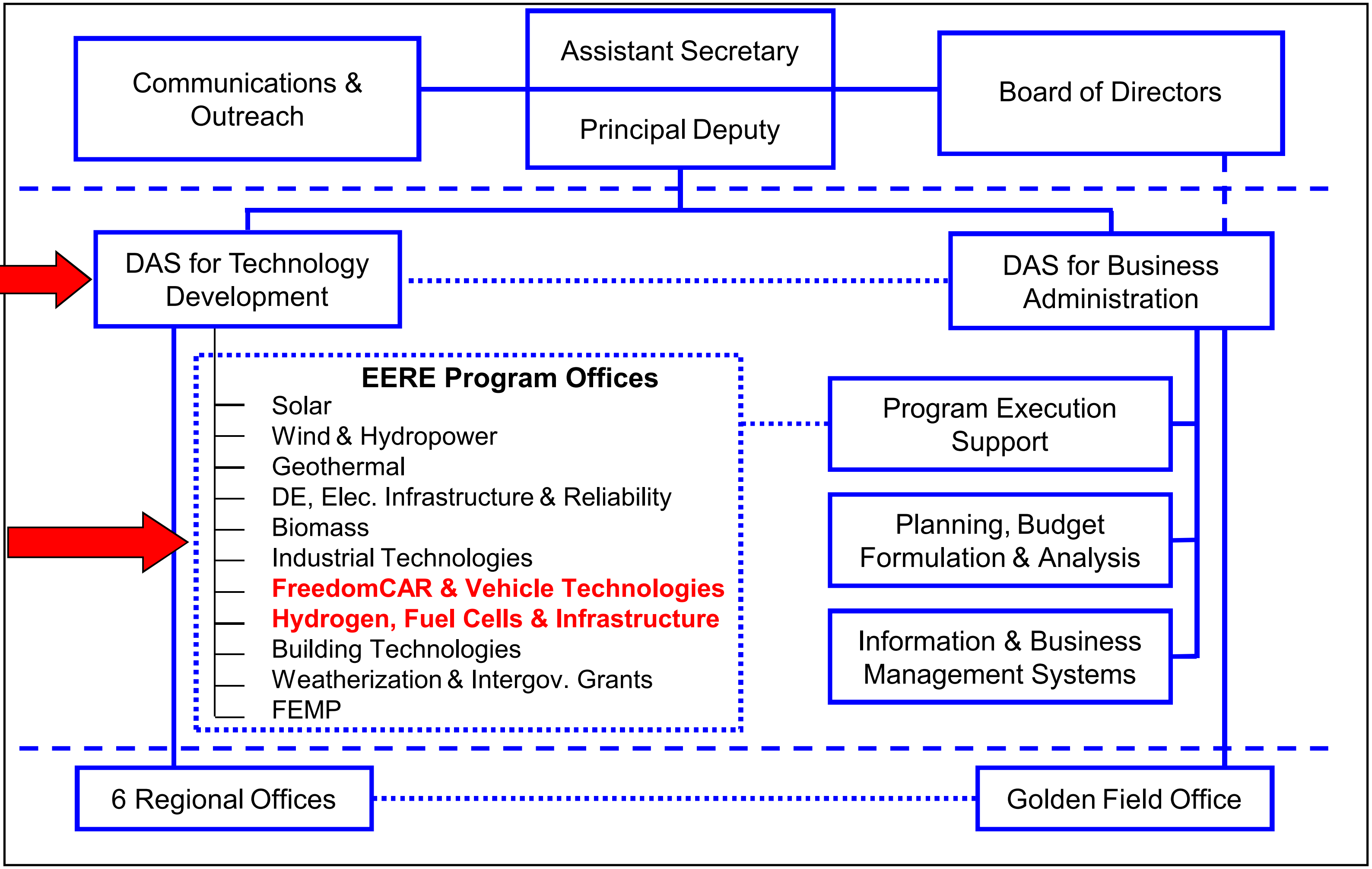
The Goals

The general goal is to develop technologies that enable cars and trucks to become highly efficient, through improved power technologies and cleaner domestic fuels, and to be cost and performance competitive. Manufacturers and consumers will then use these technologies to help the nation reduce both energy use and greenhouse gas emissions, thus improving energy security by dramatically reducing dependence on foreign oil. The benefits will include saving 4 to 6 million barrels of oil per day, reducing greenhouse gas emissions by 50%, and enabling U.S. manufacturers to be competitive in the global market.

DOE Energy Efficiency and Renewable Energy (EERE) Office

Two DASs

Eleven Program Offices



FreedomCAR Program Structure

FreedomCAR is a Partnership between the DOE and Ford, General Motors, and Chrysler

- **Developer Program: US Advanced Battery Consortium (USABC)**
  - Develop electrochemical energy storage devices that meet USABC/FreedomCAR technical goals through cost-shared projects with industry
- **Applied Battery Research: Advance Technology Development (ATD) Program (now ABRT program)**
  - Address key cross-cutting barriers for lithium ion batteries to support the Developer Program
- **Focused Fundamental Research: Batteries for Advanced Transportation Technologies (BATT) program**
  - Conduct innovative, cutting-edge research on the next generation of lithium battery systems

(Sandia Program Participation)

DOE Advanced Technology Development (ATD) Program

DOE's Advanced Technology Development (ATD) Program addresses the three barriers that remain for batteries in hybrid electric vehicles -

- high cost, short calendar life, and poor abuse tolerance.

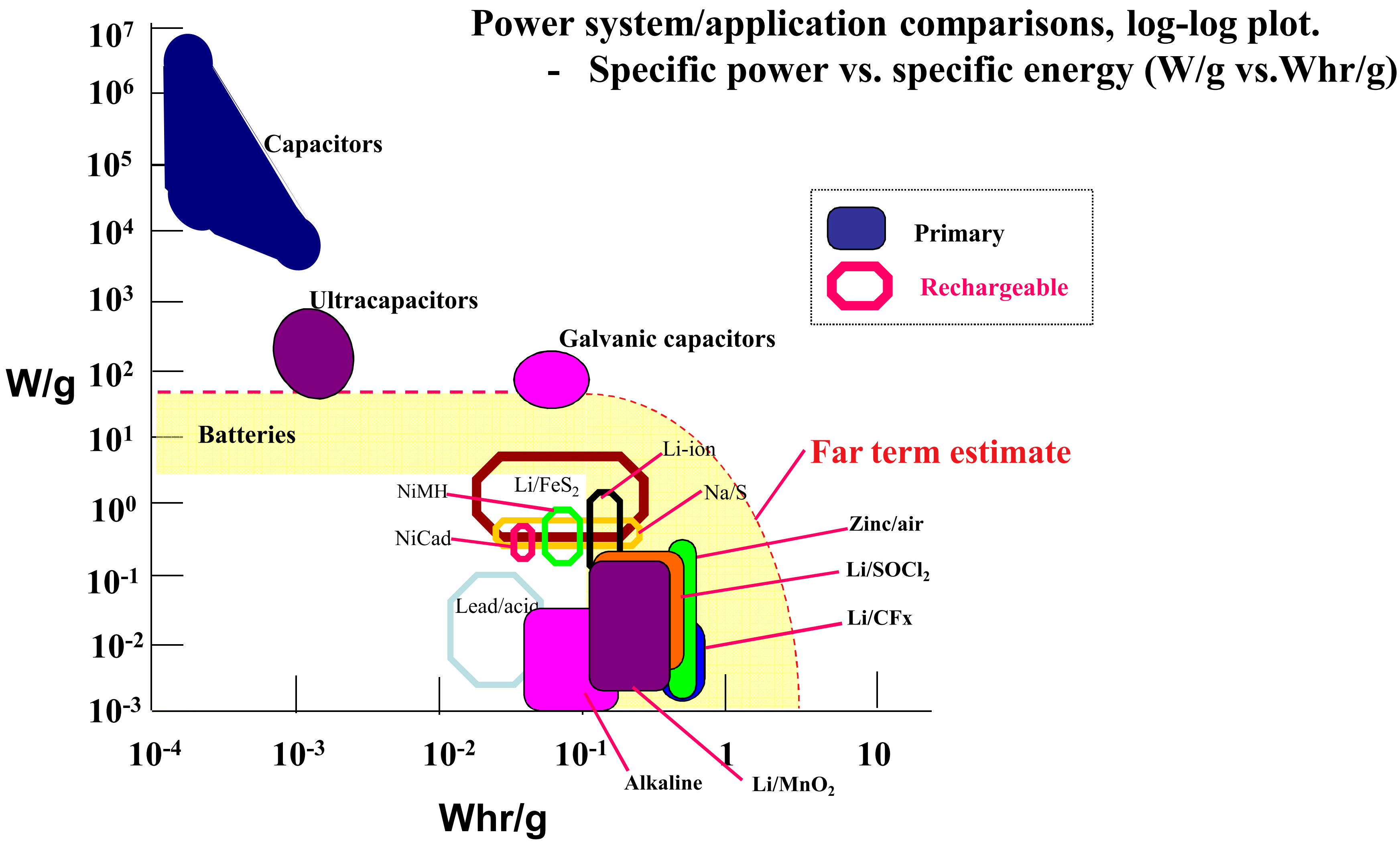
- Involves 6 US National Laboratories and 1 DoD Lab
  - Argonne National Lab, Sandia National Labs, Lawrence Berkeley National Lab, Idaho National Lab, Brookhaven National Lab, National Renewable Energy Lab and Army Research Lab

- Technical goal is to
  - Develop improved diagnostic techniques at National Labs.
  - Identify life-limiting mechanisms for failure of lithium-ion cells during abuse and aging

Sandia FreedomCAR Mission

- **Provide Abuse Testing and Characterization of Advanced Cells and Batteries to Enable Development of Abuse Tolerant Cell Chemistries and Designs**

Li-Ion Cells Offer the Highest Energy and Power Densities of the Rechargeable Chemistries



Proliferation of Types of HEVs – Batteries Serve Many Different Functions

Types of HEVs	1	2	3	4	5	6	7	8
Category	**Micro-1**	**Micro-2**	**Micro-3**	**Mild-1**	**Mild-2**	**Mild-3 "Boost"**	**Moderate**	**Full HEV**
Main Attribute	Stop Crank	Cold Start	Stop-Crank-Regen	Regen-Launch Assist	Regen-Launch Assist	Launch Boost	Power Assist	Extended Power Assist
Type of Car	Small Car	Large and Luxury Car	All	All	All	Sporty	All	All
Electric Machine	Belt Driven	Starter or Belt Driven	Belt Driven	Belt Driven or Crank Shaft	Crank Shaft	Crank Shaft	Crank Shaft	Crank Shaft
Power Level (for mid-size car)	2 to 5 kW	2 to 5 kW	4 to 7 kW	4 to 8 kW	6 to 12 kW	12 to 30 kW	12 to 30 kW	25 to 60 kW
Operating Voltage	14 V	14 V up to 42V	14 V	42 V	42 V	42 V to 60V	42 V to 150V	150 V to 600V
Example	PSA C3	Not Yet	Not Yet	GM Silverado	Not Yet	Not Yet	Civic	Prius & Escape
Cold Engine Crank by Hybrid Battery					Desired	Desired	Desired	Desired
Stop/Start cranking								
Regenerative Braking								
Alternator Assist								
Crank to Idle Speed								
Torque Smoothing/ Shift Assist								
All Wheel Drive								
Launch Assist								
Power Assist								
Electric Drive								

Keys for Color Coding	
Provides the Function	
Limited Function	
Moderate Function	
Extended Function	

Micro = no propulsion
Mild = Minimal propulsion
Moderate & Full = battery provides vehicle propulsion

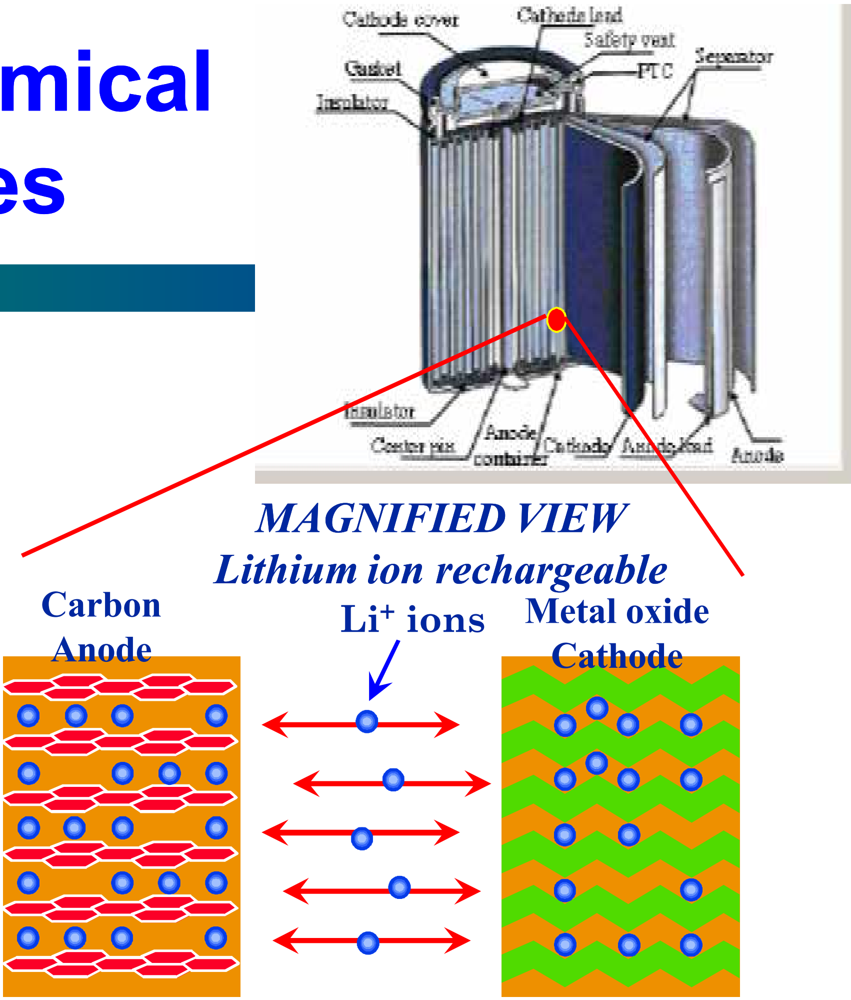
Adapted from M. Anderman, Adv. Auto Battery Conf. June 2005

Li-Ion Cells are Already Entering the EV Market

The Tesla Roadster

- 0-60 mph acceleration: <4 seconds
- EPA highway driving range: >250 mi.
- Well-to-wheel efficiency: >135 mpg
- Equivalent Driving cost: About 1 penny per mile
- Charging infrastructure: existing electric service
- Tesla Motors designed: 50 kWh lithium ion battery pack
- 185 kW AC induction motor
- 200 kW Power Electronics Module
- Carbon fiber body
- Bonded, extruded aluminum chassis

Li-Ion Electrochemical Power Sources



The fundamental bases of electrochemical power sources are chemistry and physics.

- **Materials - cathode, anode, electrolyte, solvent, separator**
- **Synthesis of these materials**
- **Charge transfer reactions**
- **Ion mobility & charge compensation *(diffusion, migration, convection)***
- **Reaction kinetics**
- **Thermodynamics**

Charge reactions, one at the anode and one at the cathode

(1) $Li_{1-x}C_6 + xLi^+ + xe^- \longrightarrow LiC_6$ (2) $LiCoO_2 \longrightarrow xLi^+ + xe^- + Li_{1-x}CoO_2$

Discharge reactions, one at the anode and one at the cathode

(1) $LiC_6 \longrightarrow Li_{1-x}C_6 + xLi^+ + xe^-$ (2) $xLi^+ + xe^- + Li_{1-x}CoO_2 \longrightarrow LiCoO_2$

Electrons and lithium ions move in both solids (solid state diffusion, electron hopping, percolation…)
Lithium ions shuttle back and forth through the solution between electrodes during charge and discharge.
Electrons also shuttle back and forth between the electrodes but through the outside circuit.

Abuse Tolerance

Abuse Tolerance Must Be Demonstrated by the New Li-Ion Chemistries Before Large Scale Commercial Application

- Thermal Abuse (over-temperature)
- Mechanical Abuse (crush, penetration)
- Electrical Abuse (short circuit, overcharge, over-discharge)

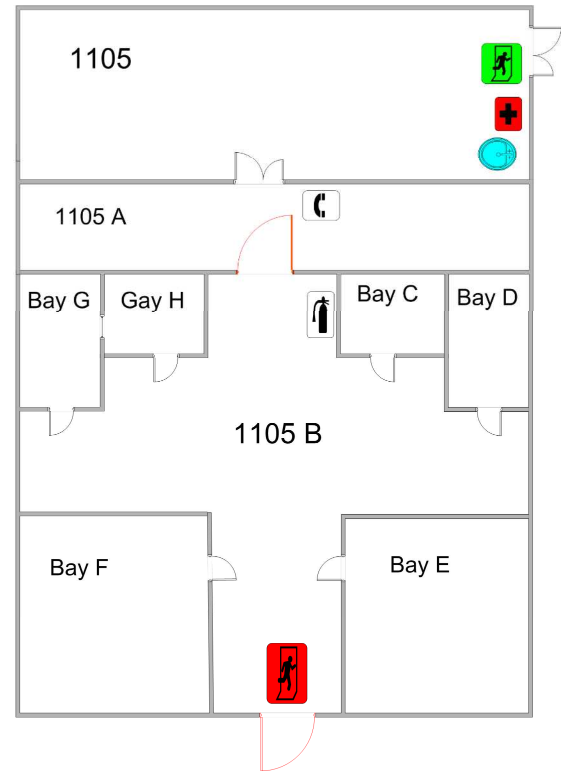
Main Areas of Research

- Effect of materials on thermal runaway
  - New anode and cathode materials
  - Electrolytes and additives
- Overcharge response
  - Effect of anode and cathode materials
  - Separator properties
  - Heat and gas generation
- Separators
  - Effect of loss of melt integrity
  - High voltage standoff

Battery Abuse Testing is Done at SNL's Explosives Component Facility (ECF)

6 Test Bays Devoted for Abuse Testing

Explosives Component Facility (ECF)



Sandia National Laboratories
Albuquerque, NM

Examples of Sandia Abuse Laboratory Capabilities

Module Crush

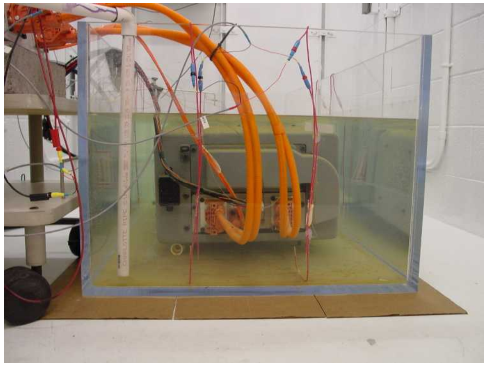
Cell Crush

Thermal Ramp

Simulated Fuel Fire

Overcharge

Accelerating Rate Calorimetry



Water Immersion

Sandia Goals and Objectives

Abuse Tolerance

- Determine response of cells to thermal abuse and overcharge
- Show relationship between abuse tolerance and chemistry
- Support experimental observations with a physical understanding through advanced diagnostics
- Investigate advanced chemistries to overcome abuse tolerance issues
- Support hypotheses through chemical modeling

Cell Chemistries Evaluated in ATD Program

- **Cathode materials:**
  - $LiCoO_2$
  - $LiNi_{0.85}Co_{0.15}O_2$ (Gen1)
  - $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (Gen2)
  - $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$; $Li_{1.1}(Ni_{1/3}Co_{1/3}Mn_{1/3})_{0.9}O_2$ (Gen3)
  - $LiMn_2O_4$ (Spinel)
  - $LiFePO_4$
- **Anode materials:**
  - MCMB (Gen1 and 3)
  - MAG10 (Gen2)
  - GDR (Gen2)
- **Electrolytes/salts:**
  - EC:EMC (3:7) 1.2M $LiPF_6$
  - EC:PC:DMC (1:1:3) 1.2M $LiPF_6$
  - LiBOB, LiBETI
- **Additives:**
  - SEI enhancer – Vinyl ethylene carbonate (VEC); Vinylene carbonate (VC)
  - Flame retardants– e.g. Phosphazene-based "Phoslyte" from Bridgestone; phosphate TPP; …

Sandia 18650 Cell Build Capability for Thermal Abuse Tolerance Studies

All Cells Built at Sandia Using Custom Coated Electrodes in the 18650 Configuration

Winder System

Li-Ion Cell Abuse Response Can Be Very Energetic

Overcharge Test

Over-Temperature Test

Pack Level Abuse Response Can Result in Multi-Cell Reactions

These pictures were taken after overcharge of a prototype HEV module at SNL Abuse Test Labs.

Testing Programs

- Testing is performed in support of several government agencies including DOE, DOD, DOT and NASA.
- Testing is also available on a limited basis to battery developers and OEMs on a Work for Others (WFO) contract basis.

Examples of WFO Projects Competed or In Progress

- Nissan Motors (Pack tests)
- SK Corp. (Pack tests)
- Hitachi (Pack tests)
- A123 (Cell tests)
- Enerdel (Cell tests)
- Quallion (Cell tests)
- Eaton Corp. (Pack tests)
- Air Products (Electrolyte tests)
- Exxon/Tonen (Separator tests)
- Dow Chemical (Electrolyte tests)
- Solvay (Electrolyte tests)
- University of Rhode Island (Cell tests)

Future Battery Abuse Response Issues

- Intrinsic abuse tolerance of Li-Ion cells required for any battery design
    - Goal is graceful failure.
- Understanding chemical response to abuse can point the way to better materials.
    - More stable electrode materials & additives
    - Control heat & gas generation as well as lower flammability
- ***No "magic bullet" for completely stable Li-ion cells***
    - Thermal abuse tolerance will result from informed choices of improved cell materials, additives and cell design.
    - Good engineering practices are essential.