I. INTRODUCTION

Vehicle Technologies Program Overview

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I. INTRODUCTION

I.A Vehicle Technologies Program Overview

The Department of Energy's (DOE's) Vehicle Technologies Program (VTP) develops advanced transportation technologies that would reduce the nation's use of imported oil. Technologies being supported by VTP include electric drive components such as advanced energy storage devices (batteries and ultracapacitors), power electronics, and drive motors; as well as advanced structural materials, and advanced combustion engines and fuels[1]. VTP works with the U.S. automakers through the United States Council for Automotive Research (USCAR)—an umbrella organization for collaborative research among Chrysler LLC, Ford Motor Company, and General Motors Company[2]. Collaboration with automakers through the US DRIVE (Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability) Partnership enhances both the relevance and the potential for success of these programs. This partnership is focused on funding high-reward/high-risk research at national laboratories, universities, and with industry, that promises improvements in critical components needed for more fuel efficient and cleaner vehicles.

The U.S. government continued its strong R&D support of plug-in electric vehicles (PEVs) such as plug-in hybrids, extended range electric vehicles and all-electric vehicles. As the global competition to develop affordable, high performance and durable PEV batteries has accelerated, the DOE has ramped up the VTP battery R&D funding from $25 million in 2006 to $93 million in 2012. In March 2012, President Obama announced the EV Everywhere Grand Challenge. A primary objective of the EV Everywhere Grand Challenge is to enable American innovators to rapidly develop and commercialize the next generation of technologies that will achieve the PEV cost, range, and charging infrastructure necessary for widespread adoption. Significant commercialization of PEVs into the nation's transportation sector offers the possibility of reducing our dependence on foreign oil and the negative economic impacts of crude oil price fluctuations, and reducing the Nation's greenhouse gas emissions.

An important step for the electrification of the nation's light duty transportation sector is the development of more cost-effective, long lasting, and abuse-tolerant PEV batteries. In fiscal year 2012, battery R&D work continued to focus on the development of high-energy batteries for PEVs and very high power devices for hybrid vehicles. This document provides a summary and progress update of the VTP battery R&D projects that were supported in 2012. An electronic version of this report can be accessed at http://www1.eere.energy.gov/vehiclesandfuels/resources/ fcvt_reports.html.

I.B Vehicle Technologies Battery R&D Overview

I.B.1 DOE Battery R&D Goals and Technical Targets

The *EV Everywhere* Grand Challenge[3] establishes a vehicle-level framework in which the technological progress toward achieving the Grand Challenge objectives can be evaluated. Batteries, power electronics, motors, lightweight materials and vehicle structures must see dramatic advances. Performance and cost targets have been established for key technical areas of a PEV. Achieving these targets will meet the needs for a range of vehicle types including plug-in hybrids as well as short and long range all-electric vehicles. A set of technology targets for PEV batteries is shown below in Figure I - 1. These targets were derived from modeling and hardware-in-the-loop simulations of batteries operating in PEVs under multiple drive cycles.

[1] See http://www1.eere.energy.gov/vehiclesandfuels/ for more information.
[2] For more information, please see http://www.uscar.org/guest/view_partnership.php?partnership_id=1.
[3] For more information, please see http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/ev_everywhere.html.

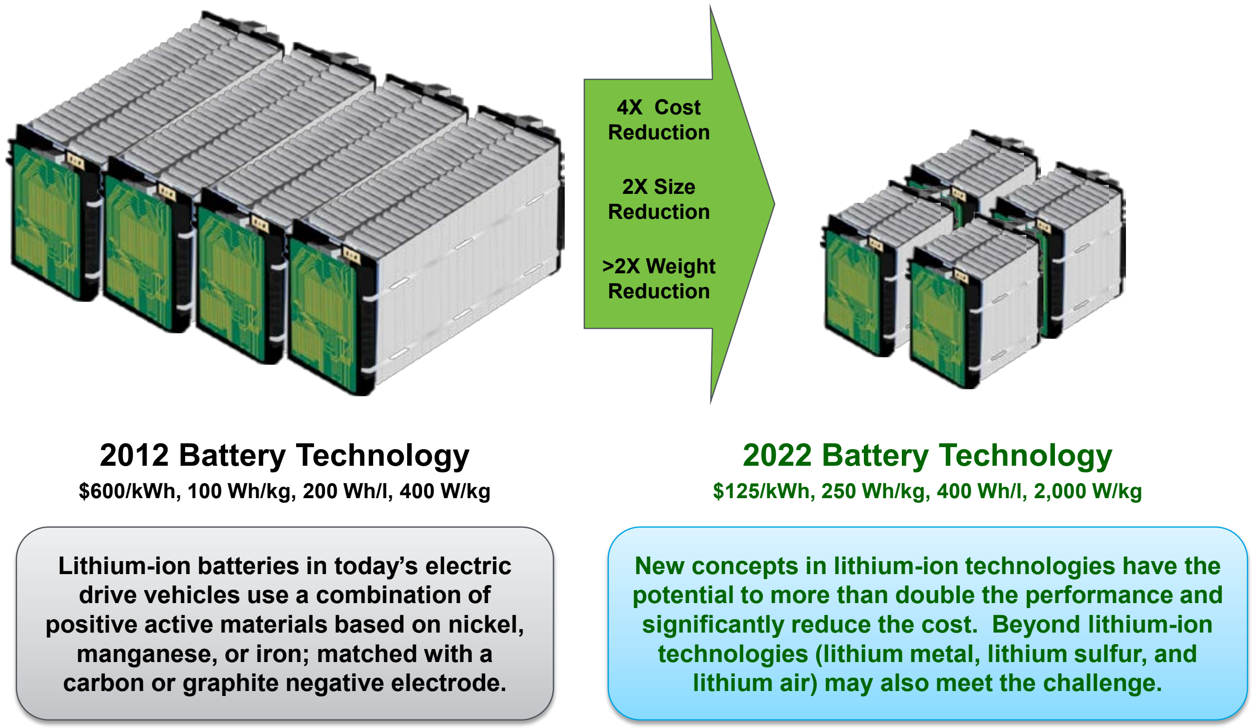


Figure I - 1: Battery advancements needed to enable a large market penetration of PEVs.

I.B.2 DOE Battery R&D Plans

The objective of the battery R&D effort within VTP is to advance the development of batteries to enable a large market penetration of hybrid and electric vehicles. Program targets focus on overcoming technical barriers to enable market success including: (1) significantly reducing battery cost, (2) increasing battery performance (power, energy, durability), (3) reducing battery weight & volume, and (4) increasing battery tolerance to abusive conditions such as short circuit, overcharge, and crush.

Current battery technology is very far below its theoretical limit. In the near-term (2012-2017), within existing lithium-ion technology, there is an opportunity to more than double the battery pack energy density from 100 Wh/kg to 250 Wh/kg through the use of new high-capacity cathode materials, higher voltage electrolytes, and the use of high capacity silicon or tin-based intermetallic alloys to replace graphite anodes. Despite current promising advances, much more R&D is needed to achieve the performance and lifetime requirements for deployment of these advanced technologies in PEVs.

In the longer term (2017-2027), battery chemistries "beyond Li-ion", such as lithium-sulfur, magnesium-ion, zinc-air, lithium-air, and other advanced chemistries, offer the possibility of specific energies that are significantly greater than current lithium-ion batteries as well as the potential for greatly reducing battery cost. However, major shortcomings in cycle life, power density, energy efficiency, and/or other critical performance parameters, including cost, currently stand in the way of commercial introduction of state-of-the-art "beyond Li-ion" battery systems. Breakthrough innovation will be required for these new battery technologies to enter the market.

The energy density increases described above will be critical to achieving the *EV Everywhere* cost and performance targets. Additional R&D efforts, including pack design optimization and simplification, manufacturing improvements at the cell and pack level, materials production cost reduction, and novel thermal management technologies will also contribute to battery cost reduction. Major technical challenges and their potential pathway to overcoming these barriers are shown in Table I - 1.

Table I - 1: Major Li-ion technology technical challenges and potential pathways to address them.

Barrier/Challenge	Potential Solutions
• Reduce the cost and improve the performance of Li-ion battery technology	• Improved material and cell durability • Improved energy density of active materials • Reduction of inactive material • Improved design tools/design optimization • Improved manufacturing processes
• Develop higher energy battery technology such as next generation lithium ion, lithium-sulfur and lithium-air o Issues with these materials include poor cycle life, low power, low efficiencies, and safety	• Improved electrolyte/separator combinations to reduce dendrite growth for Li metal anodes • Advanced material coatings • New ceramic, polymer, and hybrid structures with high conductivity, low impedance, and structural stability
• Improve abuse tolerance performance of battery technology	• Non-flammable electrolytes • High-temperature melt integrity separators • Advanced materials and coatings • Improved understanding of reactions • Battery cell and pack level innovations such as improved sensing, monitoring, and thermal management systems

I.B.3 Energy Storage R&D Programmatic Structure

The energy storage effort includes multiple activities, from focused fundamental materials research to battery cell and pack development and testing. The R&D activities involve either short-term directed research by commercial developers and national laboratories, or exploratory materials research, generally spearheaded by the national laboratories and universities. There are three major inter-related and complementary program elements, namely:

- Advanced Battery Development, System Analysis, and Testing
- Applied Battery Research (ABR)
- Focused Fundamental Materials Research, or Batteries for Advanced Transportation Technologies (BATT)

The *Advanced Battery Development, System Analysis, and Testing program*'s goal is to support the development of a U.S. domestic advanced battery industry whose products can meet electric drive vehicle performance targets. R&D in this activity focuses on the development of robust battery cells and modules to significantly reduce battery cost, increase life, and improve performance. The activity takes place in close partnership with the automotive industry, through our cooperative agreement with the United States Advanced Battery Consortium (USABC). DOE also works in close collaboration with USABC to develop battery and ultracapacity requirements for various vehicle types[4] and test procedures[5]. In FY 2012, the USABC supported 13 cost-shared contracts with developers to further the development of batteries for PEVs and HEVs. DOE also works directly with battery and material suppliers via National Energy Technology Laboratory (NETL) contracts. In FY2012, NETL managed 21 battery R&D contracts. Benchmark testing of emerging technologies is performed to remain abreast of the latest industry developments. Battery technologies are evaluated according to USABC Battery Test Procedures Manuals for the relevant EDV applications[6,7,8]. Additional R&D involves the development of innovative technologies to reduce the cost of thermal management systems, enhance battery tolerance to abusive conditions, and the development of computer aided engineering tools to enable battery design optimization. Within this report, Chapter III focuses on the battery development program.

[4] See http://www.uscar.org/guest/article_view.php?articles_id=85
[5] See http://www.uscar.org/guest/article_view.php?articles_id=86
[6] United States Advanced Batteries Consortium, USABC Electric Vehicle Battery Test Procedure Manual, Rev. 2, U.S. Department of Energy, DOE/ID 10479, January 1996.
[7] U.S. Department of Energy, PNGV Battery Test Procedures Manual, Rev. 2, August 1999, DOE/ID-10597.
[8] United States Council for Automotive Research, RFP and Goals for Advanced Battery Development for Plug-in Electric Vehicles, http://www.uscar.org/.

The *Applied Battery Research* (ABR) activity is focused on the optimization of next generation, high-energy lithium-ion electrochemistries that incorporate new battery materials. The emphasis of ABR is to identify, diagnose, and mitigate issues that impact the performance and life of cells containing advanced materials. The ABR program investigates the interaction between all cell components that can impact performance and life, including the cathode, anode, electrolyte, binders, conductive additives, and separator. The typical issues associated with incorporating new material developements into working PEV cells include: (1) inadequate power capability needed to meet the requirements of PEVs, (2) insufficient cycle life stability to achieve the 3,000 to 5,000 "charge-depleting" deep discharge cycles, and (3) poor performance at lower temperatures. The work is carried out by a team headed by the Argonne National Laboratory (ANL) and involves five other national labs, and multiple universities. Chapter IV lists all the projects which are being conducted under the Applied Battery Research activity.

The *Focused Fundamental Materials Research* activity, also called the Batteries for Advanced Transportation Technologies (BATT) activity, addresses fundamental issues of materials and electrochemical interactions associated with lithium batteries. It attempts to develop new and promising materials, to use advanced material models to predict failure modes, and scientific diagnostic tools and techniques to gain insight into why material and systems fail. It emphasizes the identification and mitigation of failure modes, coupled with materials synthesis and evaluation, advanced diagnostics, and improved electrochemical models. Battery chemistries are monitored continuously with periodic substitution of more promising components based on advice from within this activity, from outside experts, and from the assessments of world-wide battery R&D. The work is carried out by a team headed by the Lawrence Berkeley National Laboratory (LBNL) and involves several other national labs, universities, and commercial entities. The program is also studying issues critical to the realization of beyond Li-ion technologies. Two of the most promising such technologies, Lithium/Sulfur and Lithium/Air, require the use of a lithium metal anode. The main focus is to devise new methods to understand and stabilize lithium metal anodes (against mossy Li formation and dendrites) to bring about leaps in energy density without compromising durability and safety. Chapter V lists all the projects which are part of the Focused Fundamental Research activity.

Several Small Business Innovation Research (SBIR) contracts are also supported by VTP, in addition to the R&D described above. SBIR projects have been the source of new ideas and concepts. These SBIR projects are focused on the development of new battery materials and components.

Dramatic improvements in battery performance and cost will require a well-coordinated effort across all of the DOE complex and with America's most innovative researchers and companies. Coordination within DOE and with other government agencies is a key attribute of the VTP energy storage R&D effort. VTP coordinates efforts on energy storage R&D with the DOE Office of Science, the DOE Office of Electricity, and the Advanced Research Projects Agency – Energy (ARPA-E). Innovations in battery technology occur as a result of fundamental investigations carried out at national labs and universities supported by the DOE Office of Science, through translational research sponsored by ARPA-E, and through applied research and development at labs, universities and industry supported by VTP. Innovations coming from R&D on pre-competitive technologies will be transferred to and implemented by industry partners as a business case develops for these technologies through the US DRIVE public/private partnership. The USABC makes cost-shared, competitively awarded projects to industry to facilitate commercialization of pre-competitive technologies and introduce them into the marketplace.

VTP also has established extensive and comprehensive ongoing coordination efforts with other government agencies in energy storage R&D. Such efforts include membership and participation in the Chemical Working Group of the Interagency Advanced Power Group (IAPG), active participation in program reviews and technical meetings sponsored by other government agencies, and coordinating the participation of representatives from other government agencies in the contract and program reviews of DOE-sponsored efforts. DOE also coordinates with the Department of Transportation/National Highway Traffic Safety Administration (DOT/NHTSA), the Environmental Protection Agency (EPA), and with the United Nations Working Group on Battery Shipment Requirements. Additional international collaboration occurs through a variety of programs and initiatives. These include: the International Energy Agency's (IEA's) Implementing Agreement on Hybrid Electric Vehicles (IA-HEV), the eight-nation Electric Vehicle Initiative (EVI), and the Clean Energy Research Center (CERC) bilateral agreement between the US and China.

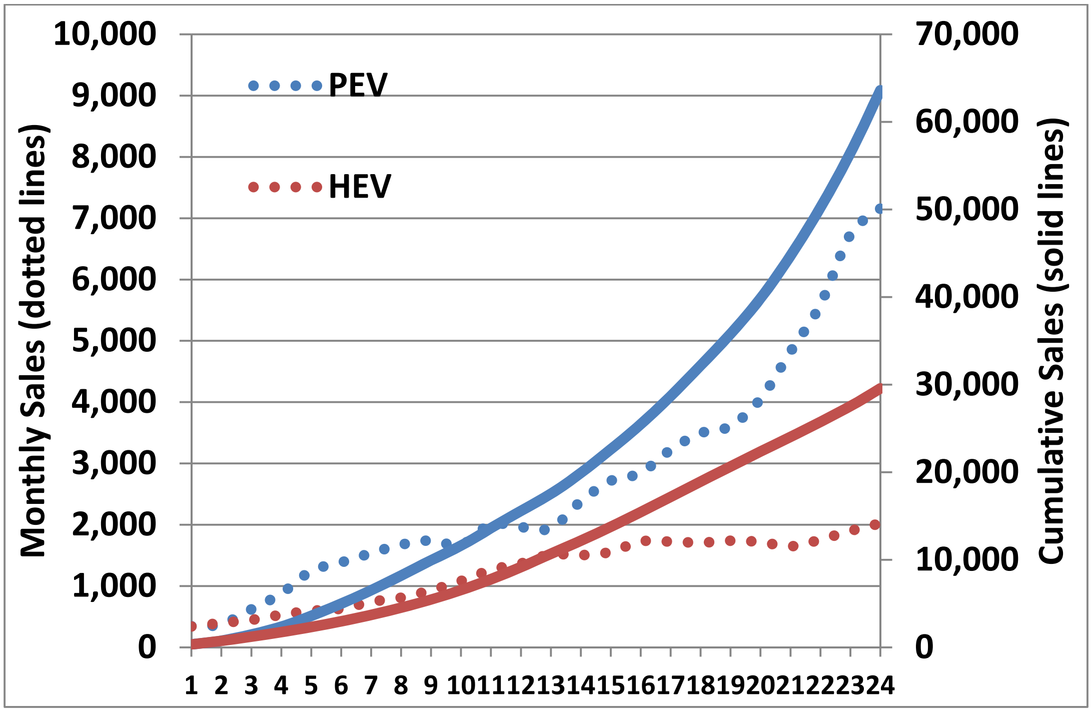
I.B.4 Recent Energy Storage Highlights

This section contains brief summaries of some key technical accomplishments in FY 2012 resulting from the VTP Energy Storage R&D and associated efforts – each one selected from many active projects and each representing a significant breakthrough of one kind or another occurring during the year.

Electric Drive Vehicle Market

U.S. sales of electric drive vehicles tripled in 2012. The EV Everywhere Grand Challenge remains focused on overcoming barriers to widespread market acceptance of PEVs, with cost reduction being a primary component. Despite obstacles, the electric-drive vehicle market is growing. Evidence of this can be seen in vehicle sales and increased investment by auto makers (see Figure I - 2).

- PEV sales are growing rapidly with 2012 U.S. sales being over 50,000 vehicles, three times the 2011 sales.
- Popular plug-in hybrid vehicle models are outselling more than half of all vehicle models available for sale in the U.S.
- Fifteen new hybrid, plug-in hybrid and all-electric vehicles are expected for production by nine different automakers in model years 2013 and 2014.



(Source: HybridCars.com)

Figure I - 2: New PEV sales compared to hybrid electric vehicle (HEV) sales over their respective 24 month introductory periods.

Commercial applications of DOE-supported technologies. Several technologies, developed partially under VTP-sponsored projects, have moved into commercial applications. Hybrid electric vehicles on the market from BMW and Mercedes are using lithium-ion technology developed under projects with Johnson Controls–Saft (JCS). Lithium-ion battery technology developed partially with DOE funding of a USABC project at LG Chem is being used in GM's Chevrolet Volt extended-range electric vehicle and has been selected for the upcoming Ford Focus EV battery. LG Chem will also supply Li-ion batteries to Eaton for hybrid drive heavy vehicles. Johnson Controls-Saft continued to supply Li-ion battery packs to Azure Dynamics for electric delivery vans built on the Ford Transit Connect platform. A123Systems is producing lithium-ion battery systems for the Fisker Karma EV and the Navistar Modec Electric trucks. A123Systems has been selected to supply lithium-ion batteries for use in the GM Spark EV, the BMW ActiveHybrid 5 and 7 models, and VIA Motors electric trucks.

PEV battery cost reduction. DOE-funded research has helped bring down lithium-ion battery costs from $1000/kWh in 2008 to less than $500/kWh today.6 DOE's goals are to continue to drive down battery cost to $300/kWh by 2014, and $125/kWh by 2022.

Recovery Act facility projects initiated and production underway. In 2012, additional facilities for advanced battery and battery component manufacturing, supported by the DOE under American Recovery and Reinvestment Act

(ARRA) cost-shared grants[9], finished construction and began production. A description of the battery manufacturing grants is presented in Chapter II. Production began at several facilities, including those listed below in Table I - 2.

Table I - 2: Current Production Status for Some Battery Facilities Funded by ARRA Grants.

Facility Type	Company	Facility Location (Status)
Cell & Pack Production	A123Systems	Cathode, cell, & pack assembly, Livonia & Romulus, MI (Production established)
	Dow Kokam	Cell & pack assembly, Midland, MI (Production in pre-buy-off run)
	East Penn	Advanced Lead Acid battery in PA (Production established)
	EnerDel	Cell production & pack assembly at Fishers & Mt Comfort, IN (Commercial pack assembly – cells sourced from Korean affiliate)
	Exide	Advanced lead acid battery, Columbus, GA (Production established)
	General Motors	Battery pack assembly at Brownstown, MI (Successful start of regular production (SORP) for the Chevrolet Volt EREV battery pack)
	Johnson Controls	Cell production & pack assembly, Holland, MI (Production established)
	LG Chem, MI	Cell & pack capability, Holland, MI (Phase I facility production established)
	SAFT	Cell production, Jacksonville, FL (First production line established)
Cathode	TODA	Battle Creek, Michigan (Production established)
	BASF	Elyria, OH (Production established)
Anode	EnerG2	Albany, OR (Production established)
	FutureFuel	Batesville, AR (Production established)
	Pyrotek	Sanborn, NY (Production established)
Separator	Celgard	Charlotte, NC & Concord, NC (Production established)
	Entek	Lebanon, OR (Engineering scoping completed)
Electrolyte	Honeywell	Buffalo, NY & Metropolis, IL (Li-salt pilot plant operational)
	Novolyte (BASF)	Zachary, LA (Equipment installation)
Lithium	Chemetall Foote	Silver Peak, NV & Kings Mountain, NC (Lithium hydroxide production established)
Cell Hardware	H&T Waterbury	Waterbury, CT (Production established)

Batteries – High Energy

Reduced cost cathode materials in production. BASF scaled-up and reduced the production cost for three nickel/cobalt/manganese (NCM) cathode materials. Two materials (NCM 111 and NCM 523) are in production in BASF's plant in Elyria Ohio, and the NCM 424 will be produced in the production plant in the first quarter of 2013. NCM 111 and NCM 424 were qualified for use in EV and PHEV applications through independent cycle life testing of over 1400 deep discharge cycles. BASF also produced enough high-energy NCM material to sample to customers and research partners.

New synthesis approach for high energy cathode materials. ANL developed a new synthesis approach for the high-energy, lithium-rich, manganese-rich layered-layered cathode materials that significantly reduced voltage fade on high voltage cycling. The performance of a cathode synthesized via a Li_2MnO_3 precursor shows high capacities of ~250 mAh/g at ~C/15, and ~200 mAh/g at ~1C rates. This material displays good stability and capacity retention over extended cycling to high voltage.

High capacity hollow silicon nanofiber anodes. Stanford University developed hollow silicon nanofibers as a new approach to manage the issues of volume expansion and solid electrolyte interphase stability in Si anodes. Electrodes with the ~ 600 nm diameter fibers demonstrated over 6,000 cycles in a half cell at a 5C rate at a capacity twice that of traditional carbon anodes.

Batteries – Improved Power

Improved performance through particle morphology control. LBNL identified the importance of particle morphology on Li transport in the 5-volt nickel/manganese spinel ($LiNi_{0.5}Mn_{1.5}O_4$) cathode material. Li diffusion in

[9] http://www.whitehouse.gov/the-press-office/24-billion-grants-accelerate-manufacturing-and-deployment-next-generation-us-batter

octahedral particles with (111) facets is at least two orders of magnitude higher than that in the plate-shaped particles with the (112) facets. The study suggests that Li transport in the Ni/Mn spinel is likely limited by the movement of phase boundaries.

Improved rate capablity of high-voltage cathode material. LBNL and collaborators investigated the 5-volt nickel/manganese spinel ($LiNi_{0.5}Mn_{1.5}O_4$) cathode material. They determined that disorder of the Ni-Mn components resulted in improved rate capability and that high levels of Mn^{3+} played little role with regard to cycleability or rate. A material with high Mn^{3+} content and high Ni-Mn disorder displayed a capacity of 120-140 mAh/g at a C/10 rate, and 115-125 mAh/g at a 1C rate.

Batteries – Improved Life and Abuse Tolerance

Improved safety through ald coating. BNL used X-ray diffraction to study the stability of high energy cathode materials, with and without an Atomic Layer Deposition coating of Al_2O_3. The uncoated sample began a phase transition at ~350°C; the coated sample did so at ~450°C. The improvement in thermal stability obtained by the ALD coating may enhance the safety of the materials.

Li-Ion electrolytes with wide operating temperature ranges. The Jet Propulsion Lab (JPL) developed new electrolytes for Li-ion batteries which provide significantly improved performance at low temperature while maintaining life at high temperature. Excellent performance was observed down to -50°C, with over 75% of the room-temperature capacity being delivered at 2C rates.

New Technologies

Progress in beyond-Li-ion technologies. LBNL, ANL and ORNL have partnered to design a series of projects that utilize recent advances in ceramic electrolyte materials, polymer science, and materials characterization to stabilize lithium metal anodes. Inorganic solid state lithium-ion conductors have been proposed as protective electrolyte layers in a lithium metal cell that contains a second, liquid electrolyte in contact with the cathode. $Li_7La_2Zr_3O_{12}$ shows great promise for these applications thanks to its high lithium conductivity. The team studied the conditions that lead to impurity formation and developed a protocol to produce dense sintered membranes and thin films. The team is also studying various Li metal protective films and dopants that lead to a stable Li/electrolyte interface and permit long-term and stable cycling.

New Tools, Facilities, and Techniques

Cell fabrication using advanced battery materials. Argonne's Cell Fabrication Facility (CFF) allows promising next-generation battery materials to be tested at industrially relevant cell sizes. The CFF allows scientists to manufacture battery cells (both pouch and 18650 cells) and battery electrodes for research purposes. Dozens of cells with high-energy lithium-manganese-rich (LMR-NMO) cathodes were built in the CFF to further investigate the voltage fade phenomenon of these materials.

Scale-up of promising materials for industry evaluation. ANL's Materials Engineering Research Facility (MERF) was established to determine fast and economical ways of producing large quantities of advanced battery materials for commercial testing. A redox shuttle material, an electrolyte additive that enhances the safety of Li-ion batteries during overcharge, was scaled-up from a 1-gram bench-scale process to multi-kilogram production. The new scaled-up process costs 20 times less and generates 50 times less waste than the bench-scale process. A 10-kg batch of the high-energy lithium-rich, manganese-rich, layered-layered cathode material was also produced.

Modeling and understanding Li-ion battery performance and cost. ANL's Battery Performance and Cost (BatPaC) model was expanded to include an air-based thermal management option, improved heat generation estimation, automatic calculation of uncertainty in point cost estimate, and updated cathode material costs. Over 465 unique downloads have occurred, primarily from industrial users.

Technologies for improved safety of Li-ion batteries. TIAX developed methods to induce Li-ion cell internal shorts and thermal runaway during otherwise normal operation and is using these methods to develop technologies to improve the safety of Li-ion batteries. TIAX developed a technology to detect growing internal shorts before they become a threat to battery safety. Cell-level technologies are being developed to delay or suppress the growth of internal shorts. TIAX is maturing these technologies for implementation in vehicle-size cells and packs.

STAR-CCM+™. A Thermally Coupled Lithium-ion Battery Design Code. CD-adapco, together with Battery Design, Johnson Controls, and A123 Systems, developed computer-aided-engineering (CAE) tools for lithium-ion battery systems. The battery designer can use validated cell models, combined with geometric details of the pack hardware and cooling system, to create a high-resolution electrical and thermal pack model. An initial version of the code is available to the public.

AutoLionTM. A Thermally Coupled Lithium-ion Battery Model. EC Power developed a commercially available computer-aided-engineering (CAE) tool for large-format Li-ion cell/pack design, called AutoLionTM. The model captures the complex interaction between temperature and battery performance and simultaneously calculate thermal and electrochemical outputs.

I.B.5 Organization of this Report

This report covers all the projects currently ongoing or starting as part of the energy storage R&D effort within the Office of Vehicle Technologies. Chapter II contains information on the status of the Recovery Act energy storage projects (funded in 2009 on a one-time basis) while the annually funded R&D projects are covered separately (chapters III, IV, and V, as outlined earlier). A list of the individuals who contributed to this annual progress report or otherwise are collaborating with the energy storage R&D effort appears in Appendix A. A list of acronyms is provided in Appendix B.

We are pleased with the progress made during the year and look forward to continued work with our industrial, government, and scientific partners to overcome the remaining challenges to delivering advanced energy storage systems for vehicle applications.

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