Electrochemical Energy Storage Technical Team
Technology Development Roadmap

1 Mission

To develop electrochemical energy storage technologies which support the commercialization of fuel cell, hybrid, and electric vehicles. To meet the requirements established for these electric propulsion vehicles, including technical performance and selling price targets.

The objective of the team is to complete the development of a high-power energy storage system that meets the FreedomCAR goals of 15-year life with 25kW pulse power and $20/kW by 2010.

The specific technical targets for both general energy storage devices (batteries and ultracapacitors) and for low cost separators are shown in Tables 1 and 2 respectively.

Table 1. FreedomCAR Energy Storage Goals

FreedomCAR Energy Storage Goals		42-Volt[1]			HEV (Power-Assist)[2]		DRAFT Fuel Cell Vehicle		Ultracapacitors[3]			Battery EV	
Parameter	**Unit**	**Start-Stop**	**M-HEV**	**P-HEV**	**Low Power**	**High-power**	**Low Power**	**High-power**	**12V Start-Stop**	**42V Start-Stop**	**42V Transient Power Assist**	**Comm.[4]**	**Long Term[5]**
Discharge Pulse Power	kW	6 for 2 sec	13 for 2 sec	18 for 10 sec	25 for 10 sec	40 for 10 sec	20 for 12 sec	50(?) for (?) sec	4.2 for 2 sec	6 for 2 sec	13 for 2 sec		
Regen Pulse Power	kW		8 for 2 sec	18 for 2 sec	20 for 10 sec	35 for 10 sec	25 for 5 sec	60(?) for (?) sec			8 for 2 sec		
Engine-off Accessory Load	kW	3 for 5 min											
Recharge Rate	kW	2.4	2.6	4.5					0.4	2.4	2.6		
Cold cranking power @ -30°C (3 pulses)	kW	8 @ ≥21V for 2 sec			5 @ $\geq V_{min}$ for 2 sec	7 @ $\geq V_{min}$ for 2 sec	5 for TBD min		4.2 @ ≥7V for 2 sec	8 @ ≥21V for 2 sec			
Discharge Specific Power 80% DOD/30 sec	W/kg											300	400
Regen Specific Power @ 20% DOD/10 sec	W/kg											150	200
Power Density	W/l											460	600
Available Energy	Wh	250 @ 3 kW	300 @3 kW	700 @ 3 kW	300 @ $C_1/1$	500 @ $C_1/1$	250	3000(?)	15 @ 1 kW	30 @ 1 kW	60 @ 1 kW		
Total Energy	Wh											40,000	
Specific Energy @ C/3 Discharge Rate	Wh/kg											150	200
Energy Density @ C/3 Discharge Rate	Wh/l											230	300
Specific Power/Specific Energy Ratio	h^{-1}											2:01	

[1] FreedomCAR 42V Battery Test Manual, DOE/ID-11070, April 2003.
[2] FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles, DOE/ID-11069, October 2003.
[3] FreedomCAR Ultracapacitor Test Manual, Revision 0, DOE/NE-ID-11173, September 2004.
[4] The EV commercialization goals were developed to provide lower, possibly reachable, goals to encourage battery developers and to enable auto manufacturers to begin to enter the EV auto market. They were developed through a group effort of the three major US automakers and the TAC.
[5] USABC Electric Vehicle Battery Test Procedures Manual, Revision 2, DOE/ID-10479, January 1996.

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Parameter	Unit	Start-Stop	M-HEV	P-HEV	Low Power	High-power	Low Power	High-power	12V Start-Stop	42V Start-Stop	42V Transient Power Assist	Comm.[4]	Long Term[5]
Calendar Life	years	15			15		15		15			10	
Cycle Life	cycle	150k cycles & miles for 450k engine starts			300k cycles (of combined Baseline + 95th Percentile + 99th Percentile)		TBD		750k cycles for 150k miles				1000 DST cycles to 80% DOD
Energy Efficiency (on Cycle-Life/Load Profile)	%	90 for Zero Power Assist	90 for Partial Power Assist	90 for Full Power Assist	90 for Baseline 25-Wh Cycle	90 for Baseline 50-Wh Cycle	90		95 for UC10[6]				80 for C/3 discharge with 6-hour charge
Maximum Self-discharge	var.	20 Wh/d			50 Wh/d		50 Wh/d		4% (72 hours from V_{max})				15% / mn
Maximum Operating Voltage	Vdc	48 (Voc after 1 sec)			400		440		17	48			
Minimum Operating Voltage	Vdc	27			0.55 x Vmax		0.55 x Vmax		9	27			
Maximum System Weight	kg	10	25	35	40	60	32	65	5	10	20		
Maximum System Volume	liter	9	20	28	32	45	26	50	4	8	16		
Operating Temperature Range	°C	-30 to +52			-30 to +52		-30 to +52		-30 to +52			-40 to +50	-40 to +85
Survival Temperature Range	°C	-46 to +66			-46 to +66		-46 to +66		-46 to +66				
Selling Price @ 100,000 units/year	$	150	260	360	500	800	400	1000	40	80	130		
Selling Price @ 10,000(?) units (40 kWh)	$/kWh											<150	<100

[6] UC10 is a life cycle test that results in cycles of 10%DOD @ 100C rate, please see the FreedomCAR Ultracapacitor Requirements at http://www.uscar.org/consortia&teams/consortiahomepages/con-usabc.htm.

Table 2. Low Cost Separator Goals[7]

Parameter	Units	Goal
Sales price	$\$/m^2$	1.00
Thickness	μm	< 25
Permeability (MacMullin Number)	dimensionless	< 11
Wettability		Complete wet out in typical battery electrolytes.
Chemical Stability		Stable in battery for 10 years.
Pore size	μm	< 1
Puncture Strength		> 300 g/25.4 μm
Thermal stability		< 5% shrinkage after 60 min at 90°C
Tensile Strength		< 2% offset at 1000 psi
Skew		< 2 mm/meter
Pin Removal		Easy removal from all major brands of winding machines
Moisture Content	ppm	< 50
Shut Down Temperature	°C	100 – 110
Structural Stability	°C	≥ 200

2 Technology Status

The current status of Li-ion batteries against both HEV low-power assist and EV goals is shown in Figure 1 and Figure 2 below. As can be seen, current Li-ion batteries fulfill many of the HEV and EV requirements, although several challenges remain. Note that although there are no measurable goals for abuse tolerance, there remain multiple challenges regarding Li-ion batteries' response to abuse conditions, including overcharge, crush, and others.

[7] See http://www.uscar.org/consortia&teams/USABC/lowcostseparatorRFPI/separatorrequirements.pdf

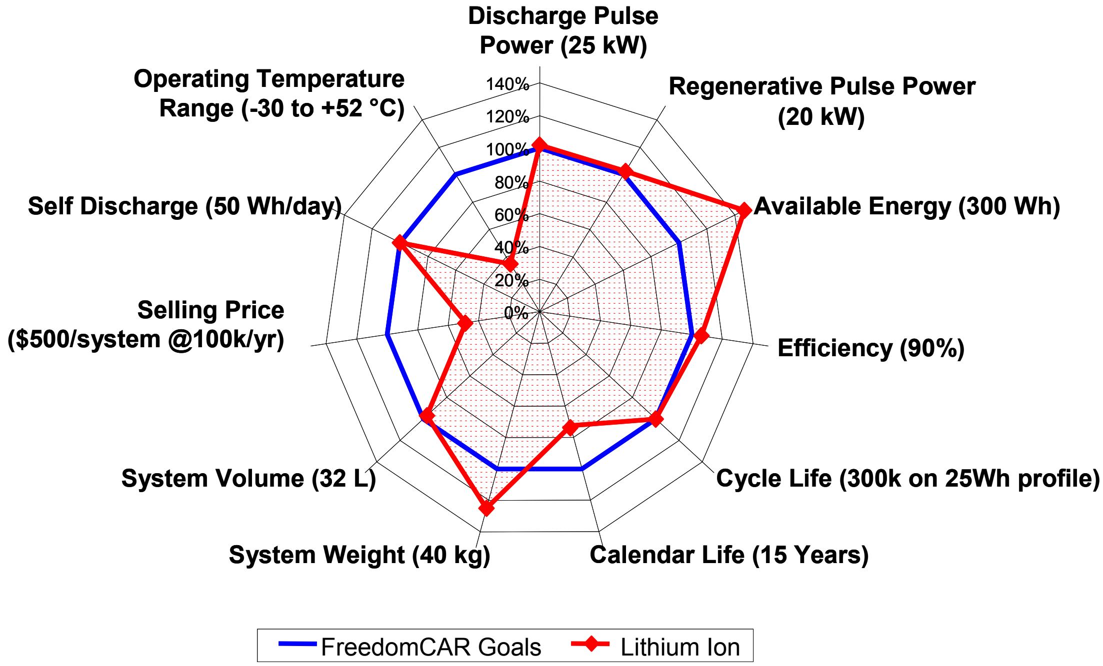

Figure 1. HEV Low-Power Assist Battery Technology Spider Chart

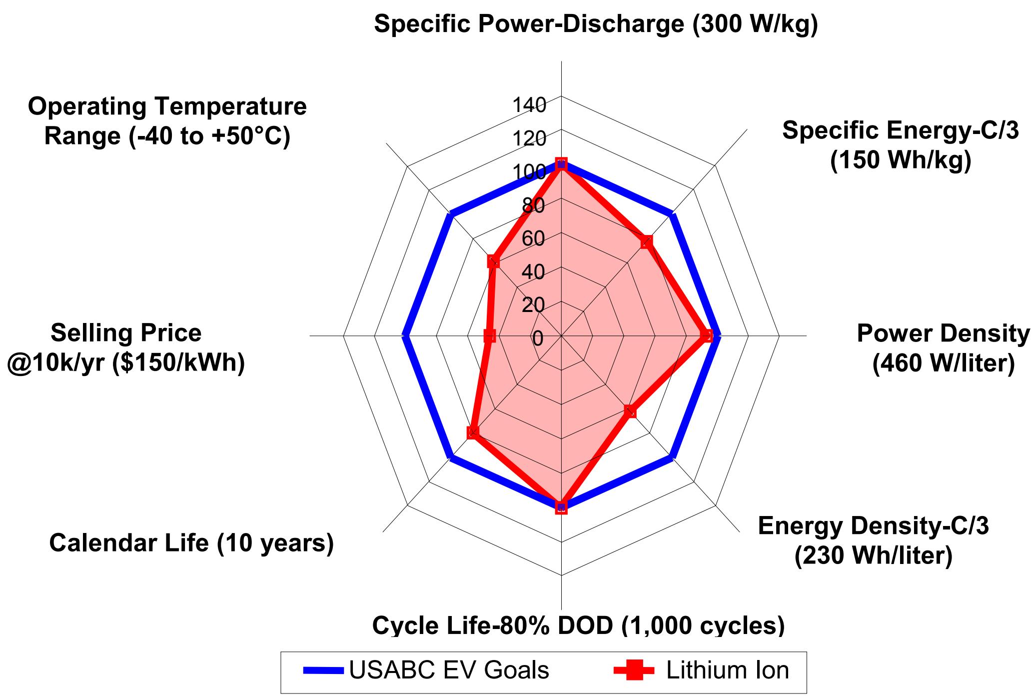

Figure 2. EV Commercialization Li-Ion Battery Technology Spider Chart

2.1 Accomplishments

Although the remaining challenges are significant, a number of impressive accomplishments have been achieved over the past five years, including:

- Increased HEV cell performance (18 sec discharge)
  - Specific Power (W/kg) = 1,344 (1999) to 1,636 (2003)
  - Power density (W/l) = 2,785 (1999) to 3,385 (2003)

- Increased cycle life of two Saft 25 kW systems to 300,000 cycles.
  - Systems used to validate Hardware-in-the Loop (HIL) testing at ANL Center for Transportation Research.
  - Cells demonstrated life of more than 1,000,000 cycles.

- Increased projected calendar life from 7 years (2000) to over 10 years (2004).

- Decreased price of 25kW battery system from:
  - $1,750 ($70/kW) in 1999 to $1,200 ($48/kW) in 2003.

- Saft (supported by USABC) has been selected by Tank-automotive and Armaments Command (TACOM) for Manufacturing Technology (ManTech) Program.

2.2 Technology Options

Given the progress and current technology status, the Electrochemical Energy Storage Technical Team selected the following technologies for further development:

(a) Li-ion and Li-ion-polymer batteries for hybrid electric vehicles
(b) Lithium sulfur batteries for high energy electric vehicles , and
(c) Ultracapacitors for high-power applications
(d) Low-cost separators for Li-ion batteries

Evaluation of emerging and advanced technologies is also actively pursued via technology assessment and benchmarking programs.

Level of Efforts among Technology Options - The current level of effort is directly proportional to the allocated budget for the individual technology. Figure 3 shows the current levels of effort to develop the candidate technologies:

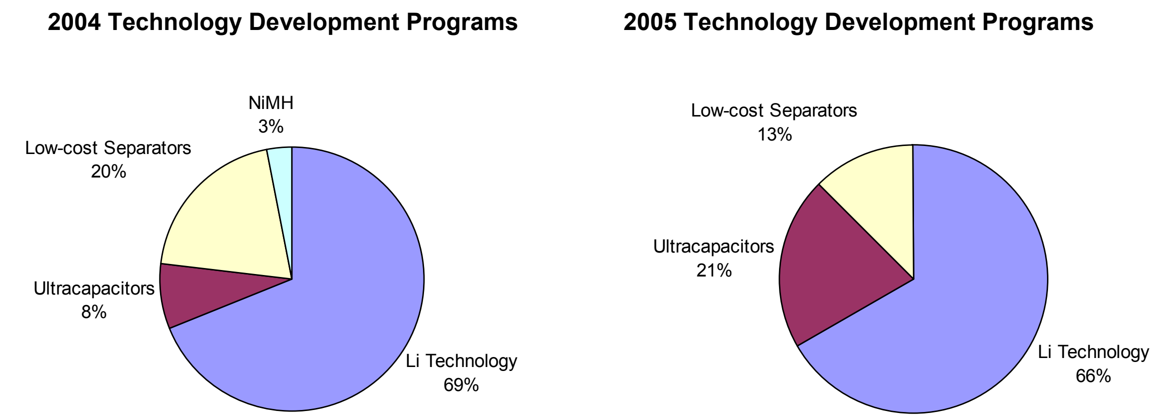

Figure 3. Level of effort by technology

3 Programmatic Strategy

Both batteries and ultracapacitors are capable of storing and delivering energy, with their performance depending on the properties of the active materials and electrolytes that constitute them. Some of these materials can store large amounts of energy by volume while others can supply it at high rates, ultracapacitors being particularly suited to high rate applications. Battery electrode design allows some flexibility in selecting performance between these two situations. The broad needs of the automobile industry range from relatively small 42V systems (requiring moderate power) that would be adequate for a vehicle designed to operate in a minimum "start/stop" mode, through the moderate size, high-power systems for use in HEVs and FCVs, to the large batteries for EVs (having high energy storage requirements). These needs will not be met with a single battery; and they may not be met with a single battery chemistry, thus ultracapacitors are also being explored.

Recently, a two-year ultracapacitor development contract with Maxwell Technologies was approved to meet the 42 V start/stop specifications. The major challenges are cost and specific energy. The Maxwell effort includes development of activated carbon, a new process for electrode fabrication, and a new cell design to address both cost and energy content challenges.

In all cases, the R&D is directed at overcoming specific technical problems to address the automotive industry needs. The R&D activities leverage all available resources, including those of automobile manufacturers, battery developers, small businesses, National laboratories, and universities to address the technical barriers preventing the introduction of advanced battery systems to the automotive marketplace. Currently, smaller, high-power batteries represent the minimum amount of increase in vehicular cost. Based on this, the Energy Storage Technical Team maximizes the effective use of available development resources by directing the bulk if its resources to small, high-power systems close to entering the market, while making the remaining resources available for other battery platforms for hardware development and testing.

Applied battery research, called the Advanced Technology Development (ATD) program, is focused on technical barriers facing the smaller battery platforms, like 42V and HEV systems, which prevent these systems from meeting all of the FreedomCAR Targets. Finally, the fundamental battery research effort, called Battery for Advanced Transportation Technology (BATT), uses a fundamental approach to address the technical barriers in the smaller systems, as well as in the larger FCV and EV systems, where the need for major changes is much greater due to more limiting fundamental barriers.

The Energy Storage Technical Team supports DOE programs and provides industry input to both the ATD and BATT programs.

3.1 Technology Development Issues

The following issues have been identified as the most critical to resolve in the proposed technology development effort.

Abuse-tolerance: High-performance energy storage systems must be intrinsically tolerant of abusive conditions: overcharge, short circuits, crush, fire exposure, over-discharge, and mechanical shock and vibration. Fail-safe responses to these conditions must be designed into the system, either at the materials or the system level, through selection of materials and mechanisms to preclude propagation of hazards.

Long calendar life: The 15-year calendar life is a severe challenge for all candidate technologies. In addition, the battery must have an extremely long cycle life at the minimum energy increment.

Operation without full recharge: The candidate technologies, both batteries and ultracapacitors, exhibit varying degrees of self-discharge. Variation in the rate of self-discharge from cell-to-cell -- due to temperature differences and manufacturing tolerances -- will cause imbalances in the cells' states-of-charge (SOC), eventually leading to over-discharge and failure of some cells. The severity of the problem remains to be determined from testing and post-test analysis of cells in long series strings.

Ambitious efficiency, weight, volume, and affordability goals: Optimization, both of the energy storage subsystem requirements -- from the vehicle systems perspective -- and of the subsystem design, must be done carefully to achieve the maximum benefits available from the component technologies. The efficiency, weight, volume, and selling price goals are shown in Table 1.

Operating temperature range: The wide range of ambient temperature will generally require active thermal management for the energy storage system. Performance of batteries and, to a lesser extent, ultracapacitors is expected to degrade at low temperatures, while system life will probably be shortened by operation at the highest temperatures.

Manufacturing processes: Advanced high-power batteries pose manufacturing issues related to:

- Fabrication and assembly of relatively thin electrode assemblies at high throughput rates
- Assembly of electrodes into compact, light-weight packages (prismatic or spiral-wound types).

Specific process developments required include the following:

- Improved bonding and sealing techniques for joining the active materials to substrates, and substrates to substrates.
- High-speed, continuous formation/handling/transfer of thin sheet materials and coatings.
- In-process control and verification of electrode film properties, including mass loading, porosity, and interconnectivity of active material particles.
- Continuous 100% monitoring of electrode and separator films for structural defects.
- High-speed cutting of thin electrode films with minimum residual material.
- Low-cost packaging of the electrode/separator assembly into cells, including attachment of electrode tabs to cell terminals and provisions for cell pressure relief.
- Production techniques for 100% inspection of cell/device sealing and electrolyte leakage.
- Module and subsystem assembly of cell stacks at high voltage.

3.2 Approaches to Resolving Development Issues

Each of the approaches described below can be summarized as follows: specific tasks begin with the establishment of technical requirements. Next, batteries available in the marketplace are evaluated against these requirements. If those requirements cannot be met, additional R&D is undertaken, in the form of advanced development, applied research, or more basic research.

Abuse-tolerance: Design of abuse-tolerant energy storage subsystems begins with specification of relevant abuse conditions and the desired responses to those conditions. USABC-sponsored development programs include initial characterizations of the candidate technologies in abuse tests. Uniform standards for characterization testing in this area have been established.

Abuse-tolerant subsystems will need to provide controls at several levels, including the vehicle controller. These controls must include detection and management of SOC, temperatures, and electrical faults. Controls at the cell level will likely include devices for relief of internal pressure buildup, and for internal circuit interruption. This latter approach must be compatible with the subsystems' functional and performance requirements.

In parallel with the lithium battery developers' efforts to provide abuse-tolerant systems, the ATD and BATT programs include work to improve the intrinsic chemical stability of lithium battery chemistries through characterization of advanced materials and development of standard abuse test protocols.

Calendar Life: This has been identified as a severe challenge for all candidate technologies, including Li-ion batteries and ultracapacitors. The expected calendar life of the baseline battery systems has been improved from initial projections of 2-4 years to over 10 years currently. Developers are investigating improved chemistries, using knowledge gained from DOE's research programs.

Operation without Full Recharge: It is unlikely that the candidate technologies can ever reduce their self-discharge, and its variability, to zero. A general approach for keeping the series-connected cells of the subsystem in balance (i.e., in an equal SOC) is to continually monitor the cells' SOCs and adjust external bleed resistances to keep the total (internal plus external) self-discharge rate in balance for all cells. Each of the cells' SOCs would be estimated from measurement of their OCVs or coulomb counting. The subsystem development plan includes characterization of self-discharge for both electrode and cell configurations, conceptual design of a compensating control system, and prove out of the concept in 50-volt modules.

Ambitious Efficiency, Weight, Volume, and Affordability: Results to date indicate that subsystem designs can be achieved that approach the FreedomCAR efficiency, weight, and volume targets. Cost, however, is a major challenge in the implementation of hybrid-electric drive trains. Production cost reductions require manufacturing process development efforts and material cost reductions. In addition to the developers' efforts within the USABC programs, DOE is continuing to sponsor research at universities and the National Laboratories for development of low-cost materials and cell packaging concepts for advanced batteries.

Operating Temperature Range: To keep a battery and perhaps an ultracapacitor within its desired operating temperature range for desired performance and life, it will be necessary to provide thermal management at the subsystem level. In a hybrid vehicle, thermal management may be integrated into the engine/power plant cooling system. The engine coolant can be circulated to the battery for two purposes -- heating the cells after the ICE has warmed the coolant, and possibly cooling the cells during sustained high-power periods and/or high ambient temperatures. In some applications it may also be necessary to integrate the battery cooling system and the air-conditioning system.

Electro-thermal modeling of cells/modules is used to aid developers in designing batteries with improved thermal performance such as reduced hot spots and uniform temperature distribution. The present module designs feature a mix of thermal management approaches.

Manufacturability for Automotive Applications: The manufacturing challenges will be addressed at the outset by the FreedomCAR developers. The developers selected by USABC are intended to be the eventual tier one automotive suppliers of energy storage systems. As full-service suppliers they are responsible for development of their supply base for materials, components, and process equipment. Meeting the systems' production cost targets will require aggressive efforts to: 1) design for minimum cost; 2) streamline manufacturing processes; and 3) increase competition among the suppliers of high-priced materials. New materials and material processes are eventually needed to reach the FreedomCAR cost targets.

3.3 General Focus Areas

The following bullets indicate a general set of tasks that the FreedomCAR Energy Storage Technical Team is focusing on and plans to continue over the next several years.

- Establish and reaffirm performance targets for batteries for 42V, HEV, FCV, and EV systems.
- Establish and reaffirm performance targets for ultracapacitors for 42V start/stop systems.
- Establish hardware development projects with qualified battery developers to develop batteries for validation testing against the technical targets.
- Perform independent validation testing of developer-supplied hardware.
- Provide guidance to DOE's applied battery research activity that focuses on immediate technical barriers inhibiting the attainment of established performance and cost targets for batteries.
- Provide guidance to DOE's basic research activities that addresses fundamental problems that impede the development of advanced batteries, develops and evaluates novel battery materials, and broadens advanced diagnostic and modeling capabilities.

Periodic reviews are conducted to ensure that all work remains appropriately focused. All development activities lead to hardware deliverables that are independently tested against the agreed-upon targets. For research activities, merit reviews are held on a yearly basis before an independent panel of battery and automotive experts to assess the quality and relevancy of all research and to provide guidance for future efforts.

3.4 Specific Task Descriptions

To implement this approach, specific tasks have been identified under the development and demonstration, applied battery research, and basic research activities, as described below.

3.4.1 Development and Demonstration

Fuel cells and batteries are based on similar underlying electrochemical fundamentals, and can theoretically be designed and constructed with comparable energy efficiencies. However, their methods of energy storage and their abilities to recapture energy are much different. Determining an appropriate mix of fuel cell and battery for an automobile is up to the individual car maker and would be based on normal temperature operation, cold temperature operation, overall system efficiency, and cost. Minimum and maximum battery performance targets have been established by the team for automotive batteries with complementary fuel cell engines.

Conventional automobile batteries can be as much as three times more energy-efficient than heat engines, even not including the additional energy recaptured through regenerative braking. As batteries assume engine functions, the overall efficiency of the vehicle would increase.

However, increasing battery size also increases the overall cost. Again, deciding an appropriate battery size will be left to individual car companies.

To optimize resources, not all of the development resources are spent in full development efforts. To evaluate technologies considered close to market, a Benchmarking activity is in place where systems are purchased directly from suppliers and independently tested by a National Laboratory. For technologies developed only on a pilot scale or smaller, a Technology Assessment activity is in place where we work with the supplier to develop hardware suitable to conduct the testing. A proposal for full development can only be considered after completing after such an assessment.

3.4.1.1 Establish Targets - The establishment of technical targets for ultracapacitors, and for 42V, HEV, EV, and FCV batteries is a critical step because it provides the development and research community clear goals for their work. Much of this work has been completed and is provided in Table 1.

3.4.1.2 Benchmark and Assess Technologies – This program is committed to the continuous evaluation of new technologies and commercial products as they become available. Data from these studies will be combined with similar data from other development contracts to identify areas for additional R&D.

3.4.1.3 Develop 42V Battery - Based on cost and the ability to meet performance targets, the Energy Storage Technical Team expects to continue its emphasis on the development of 42V systems.

3.4.1.4 Complete FCV Battery Requirements Analysis and Issue an RFPI for FCV Battery Development – The tech team will complete the analysis of requirements for an FCV battery. Next, an RFPI will be developed and advertised to attract qualified battery developers to develop hardware for validation testing against fuel cell vehicle targets.

3.4.1.5 Develop Li-ion/gel polymer battery - Continue development, with a qualified developer, to further investigate the feasibility of a Li-ion/gel polymer system - a leading candidate for meeting most FreedomCAR targets, including safety.

3.4.1.6 Develop Li/S Technology - Li/S shows great promise as a high energy battery couple. The focus of this effort will be to address the lithium/sulfur isolation issue through the development of new processes to protect the lithium anode. This project will then evaluate these processes, with one developer being chosen to continue development of the most promising technology.

3.4.1.7 Develop Low-Cost Separators - Through an independent analysis, we have determined that the cost of the separator, more than any other component in the battery today, is at a high cost due to high demand and low supply and market forces from the portable electronics and computer industries. For this reason we have started a development program with potential separator suppliers to develop low-cost separators for advanced automotive applications.

3.4.1.8 Develop Ultracapacitors – Support the development of low-cost ultracapacitors, with initial emphasis on low cost carbons and on decreasing the manufacturing cost.

3.4.2 Applied Battery Research

As described above, USABC is currently supporting the development of high-power Li-ion batteries with industry. Although industrial developers have made significant progress in developing such batteries, they have not yet demonstrated that they can meet all of the requirements in the areas of abuse tolerance, calendar life, operating temperature range, and cost. The applied battery research effort, called the Advanced Technology Development (ATD) program is directed at assisting the industrial developers to identify the major factors responsible for these barriers and to find viable solutions to them. The goal is to facilitate the development of a low-cost cell chemistry that can simultaneously meet the calendar life, performance (including low-temperature performance), abuse tolerance, and cost goals that have been established by FreedomCAR. Specific tasks are discussed below:

3.4.2.1 *Extend Calendar Life & Enhance Life Prediction* – A new cell chemistry, employing a more stable $Li_{1+x}Ni_{1/3}Co_{1/3}Mn_{1/3}O_2$ cathode material, will be studied in high-power sealed cells to assess the resulting calendar life and abuse tolerance improvements relative to the Gen 2 cell chemistry, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$. Detailed specifications for the materials used in these cells will be established. As done with prior cells, new and aged cells will be subjected to detailed diagnostic studies and the cells will be modeled electrochemically to establish the factors that control power fade. In a parallel effort, the methodologies described in the Technology Life Verification Test manual will be validated using high-power HEV cells from one of the industrial battery developers.

3.4.2.2 *Enhance Low-Temperature Performance* - Understand the factors that limit the low-temperature performance of high-power Li-ion cells and develop approaches for enhancing their performance. Identify alternative electrode materials and electrolyte components that enhance low temperature performance.

3.4.2.3 *Enhance Abuse Tolerance* - Understand the factors that limit the inherent thermal and overcharge abuse tolerance of Li-ion cell chemistries and develop approaches for enhancing their abuse tolerance. Use the knowledge gained in FY 2004 on the role of each cell component in the abuse characteristics of the Gen 2 chemistry to identify additional advanced cell materials and electrolyte additives (including flame retardants) that enhance the inherent abuse tolerance of Li-ion cells.

3.4.2.4 *Identify Low-Cost Cell Materials and Components* – Continue studying the performance and stability of the newest low-cost cell materials and components, available from international material suppliers, for their potential application in high-power HEV cells. This includes advanced anode and cathode materials, electrode additives and binders, electrolyte salts and solvents, as well as gel-polymer electrolyte technologies and low-cost flexible cell packaging. Also, assist industry in optimizing their materials and components for use in HEV applications.

3.4.3 Long-term Exploratory Research

The long-term exploratory research activity, called Batteries for Advanced Transportation Technologies (BATT), conducts fundamental focused research that will lead to next-generation

Li-ion and Li-metal batteries with superior performance, life, abuse tolerance and low cost. Specifically, the emphasis is on understanding fundamental processes and limitations, and using this knowledge to develop new and improved materials and components. This approach allows BATT to not only address the technical barriers outlined in this roadmap, but also search for the next-generation Li-battery chemistry. This work requires a steady, focused, and long-term commitment and is divided into six interrelated groups of activities: Cell Development, Diagnostics, Modeling, Anodes, Cathodes, and Electrolytes. A list of specific tasks follows.

3.4.3.1 Define Baseline Chemistry - Baseline systems for exploratory research are defined to help maintain a level of cohesiveness and provide continuous focus to the investigators. The baseline and exploratory systems are reviewed every two to three years, and revised as needed, to provide direction and cohesiveness to the investigators. Those systems are currently

- $LiNi_{1/3}Co_{1/3}Mn_{1/3}/LiPF_6$ in EC:PC:DMC / Natural Graphite
- $LiFePO_4/LiPF_6$ in EC:PC:DMC / Natural Graphite
- $LiMn_2O_4$/LiBOB in gBl:EA / Natural Graphite

3.4.3.2 Synthesize and Evaluate Novel Materials - Members of the Anodes, Cathodes, and Electrolytes groups will synthesize novel materials offering the possibility for improved cell performance, life, or cost. Research on polymers is shifting to gels where significant cost savings in battery systems can be achieved.

3.4.3.3 Assemble and Test Baseline Cells – Both baseline and novel materials acquired from the Anodes, Electrolytes, and Cathodes areas or from outside sources are assembled into laboratory cells by the Cell Development group and tested. These tests will include both high energy (EV) and high-power (HEV) screening.

3.4.3.4 Diagnose and Model Cell Behavior - The Diagnostics group will examine virgin materials, as well as materials from cycled cells, to determine failure mechanisms and characteristics of cells that perform well. The Modeling group will model the baseline systems and optimize the design of each system for those applications where it is more likely to meet performance targets. The Modeling group will also model growth of the solid electrolyte interface (SEI) layer, structural changes during cycling, and ohmic losses due to poor particle-to-particle contact.

3.4.4 Other Research

3.4.4.1 Thermal Management - In order to aid developers to improve thermal performance of energy storage devices before their final delivery, data on thermal characteristics and thermal models on designing thermal performance are needed. Thermal characteristics of batteries will be measured, thermal performance will be modeled and computer aided design tools such as electro-thermal models will be used to develop configurations with improved thermal performance. Special attention will be paid to 42V batteries for three classes of HEVs and to fuel cell systems. A large size calorimeter will be used to test 42-V liquid-cooled modules. A test procedure for testing effectiveness of thermal performance of modules and pack will be developed and Program deliveries will be evaluated against this procedure. The effectiveness of high frequency alternating current (AC) to preheat batteries at very cold temperatures will be further studied

3.4.4.2 Sub-System Modeling and Simulations - Engineers will work with energy storage developers to improve and validate energy storage models for sub-system simulations. Using existing vehicle simulation tools and developed energy storage modules, the role of batteries, ultracapacitors and their combinations will be analyzed for various electric propulsion vehicles. Researchers will use these models in optimization studies and target analyses for different platforms and vehicle types such as defining energy storage requirements for fuel cell vehicles, or determining optimum combination between ultracapacitor and battery requirements for 42V mild hybrids.