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Developments in Lithium-Ion Battery Technology in The Peoples Republic of China

Energy Systems Division

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Developments in Lithium-Ion Battery Technology in The Peoples Republic of China

by
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The following is a list of the abbreviations, acronyms, and units of measure used in this document. (Some acronyms and abbreviations used only in tables may be defined only in those tables.)

GENERAL ACRONYMS AND ABBREVIATIONS

ABAT	Advanced Battery Technologies, Inc.
ASME	American Society of Mechanical Engineers
BIT	Beijing Institute of Technology
CATARC	China Automotive Technology and Research Center
CE	Conformité Européenne (French for “European Conformity”)
DOD	depth of discharge
DOE	U.S. Department of Energy
EV	electric vehicle
GB	Guobiao
GM	General Motors (Corporation)
GRINM	General Research Institute for Nonferrous Metals
HEV	hybrid electric vehicle
IEC	International Electrical Commission
MGL	Mengguli Corporation (MGL)
MOST	Ministry of Science and Technology
NLI	nano-lithium-ion
NREL	National Renewable Energy Laboratory
OVT	Office of Vehicle Technologies Program
PHEV	plug-in hybrid electric vehicle
PLI	polymer lithium-ion
PRC	Peoples Republic of China
PV	photovoltaic

QSTC	Chemical and Physical Power Sources of China Ministry of Information Industry
R&D	research and development
RMB	Ren Min Bi
SEI	solid-electrolyte interface
SOC	state of charge
UL	Underwriters Laboratories
USABC	U.S. Advanced Battery Consortia
VRLA	valve-regulated lead-acid

OTHER ABBREVIATIONS

Li-ion	lithium-ion
$LiCoO_2$	lithiated cobalt-oxide
$LiFePO_4$	LFP; lithiated iron phosphate (olivine)
$LiMnO_2$	LMS; lithium manganese spinel
$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$	NCH; lithiated mixed oxide of nickel, cobalt, and aluminium
$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$	NCM; lithiated mixed oxide of nickel, cobalt, and manganese
NiCd	nickel cadmium
NiMH	nickel metal hydride

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SUMMARY

Lithium-ion battery technology is widely used in portable electronics products, such as cell phones, camcorders, and portable computers. At present, this technology is gaining worldwide attention as a battery option for transportation applications, including electric vehicles (EVs), hybrid vehicles, plug-in hybrid vehicles (PHEVs), fuel cell vehicles, and electric bikes in Asia.

The United States continues to lead in the research and development of lithium-ion technology. There is a strong research and development program funded by the U.S. Department of Energy and other federal agencies, such as the National Institute of Standards and Technology and the U.S. Department of Defense. However, in Asia, countries like China, Korea, and Japan are commercializing and producing this technology. China has over 120 companies involved in the production of lithium-ion battery technology. The following are highlights and conclusions based on the information provided in this report:

- Lithium-ion batteries offer higher power and energy per unit weight and volume and better charge efficiency than nickel metal hydride (NiMH) batteries. These attributes allowed them to capture a major part of the portable rechargeable battery market within a few years of their introduction and to generate global sales estimated at $5 billion in 2006.

- Battery temperature affects battery performance and life. Therefore, battery thermal management is critical to achieving desired performance and calendar life for battery packs in hybrid electric vehicles. Automakers and their suppliers are paying increased attention to battery thermal management to ensure that warranty costs for battery replacement do not exceed projections. The battery in a hybrid electric vehicle (HEV) experiences a demanding thermal environment and must be heated during cold-weather operation and cooled during extended use and during warm-weather operation.

- Mass-manufacturers of lithium-ion cells for consumer products are now engaged in the development of lithium-ion chemistries for HEV and PHEV applications, with commercialization possible as early as 2010. The major impediment to developing lithium-ion batteries for PHEVs appears to be that the PHEV battery requirements are not clearly defined at this time.

- Battery thermal management is critical to achieving performance and extended battery life in electric and hybrid vehicles under real driving conditions. To find a high-performance and cost-effective cooling system, system thermal response and its sensitivity must be evaluated as a function of controllable system parameters.

- A well-designed thermal management system is required to regulate electric vehicle (EV) and HEV battery pack temperatures evenly, keeping those within

the desired operating range. Production HEVs require an active heating/cooling battery temperature monitoring system to allow them to operate in hot and cold climates. Proper thermal design of a module has a positive impact on overall pack thermal management and its behavior.

- A key attraction of lithium-based batteries is the high cell voltage, which is the direct result of the highly negative potential of lithium. With currently used mixed oxide positives, the operating voltage range of lithium-ion cells is approximately 2.75 to 4.2 V. The nominal (average) discharge voltage is about 3.6 V, and most of the usable cell capacity is delivered between 4.0 and 3.5 V.

- The calendar life of high-power lithium-ion battery cells is expected to have the same basic dependence on temperature as high-energy cell designs, because several of the high-power cell technologies use the same basic chemistry as larger cells and thus are subject to the same kind of degradation processes.

- The current cost of lithium-ion HEV batteries made with early pilot equipment is around $2,000/kWh. If the current designs were brought to volume production, the cost is anticipated to drop to approximately $1,000/kWh.

- In the past three to four years, companies outside of the Peoples Republic of China (PRC) have been bringing advanced battery technologies to the PRC and setting up partnerships and/or joint ventures to manufacture batteries for these and other applications (such as electric bikes, EVs, and HEVs) to take advantage of low labor cost and incentives provided by the Chinese government. Companies in the PRC are very aggressive in developing manufacturing processes for the batteries export market.

- From 2001 to 2004, the number of battery companies in China increased from 455 to 613; accordingly, the number of employees in those industries also increased from 140,000 in 2001 to 250,000 in 2004. The total output reached 63.416 billion Yuan ($8.1 billion) in 2004, which is an increase of 52.58% over 2001.

- The sales of large-scale companies in the battery industry was 59.818 billion Yuan ($7.65 billion) in 2004 — this was an increase of 52.85% in comparison with 2003, an increase of 105.32% in comparison with 2002, and an increase of 160.93% in comparison with 2001. This growth is attributed to the growth of large companies. In the last four years, the debt-to-asset ratio of China's battery industry has been fluctuating between 54 and 59%.

- The most commonly used battery industry standards in China for testing and evaluating battery technologies are those from the International Electrical Commission (IEC).

- Along with the rapid growth of lithium-ion battery manufacturers in China, companies like the BYD Company Limited; Tianjin Lishen Battery Joint-Stock Co., Ltd.; Shenzhen BAK Battery Co., Ltd.; and Shenzhen B&K Technology Co., Ltd., are increasing their share of the market. In 2004, the domestic and overseas markets for lithium-ion batteries were flourishing — the export volume was 189 million units, with an increase of 16.3% in sales. As a result of the rapid increase in domestic demand, the import volume of lithium-ion batteries was 550 million units, with an increase of 23.43% in sales in 2004.

- At present, Chinese lithium-ion battery manufacturing companies are relatively well developed. Such manufacturers as the BYD Company Limited; Shenzhen BAK Battery Co., Ltd.; and Shenzhen B&K Technology Co., Ltd., enjoy a large share of the global battery market. During 2003–2004, the Chinese lithium-ion battery industry developed dramatically. The production of cobalt acid lithium and nickel acid lithium and the invention of new manufacturing techniques to extract lithium from salty lakes will drastically reduce the need to import anode materials for lithium batteries from abroad.

- Most Chinese companies are producing lithium-ion batteries for portable applications. Large companies have undertaken research and development with the help of joint ventures and/or partnerships with companies from Japan, Europe, and the United States.

- Lithium resources are abundant in China. As of 2000, China was the second largest producer of lithium in the world, and in 2004, it produced 18,000 metric tons.

- Lithium-ion battery packs for e-bikes range from 24 to 37 V and have a capacity of 5–60 A•h. The market for lithium-ion e-bikes in China is still small. In Japan and Europe, however, lithium-ion and NiMH are the dominant battery types, although annual e-bike sales (200,000/yr and 100,000/yr, respectively) are significantly less than those in China.

- Tsinghua University's focus is research on EVs, HEVs, PHEVs, and fuel cell electric vehicles (FCEVs), with an emphasis on battery applications. The university has six patents and four applications pending in China on battery thermal management, EV controller design, and electronics for vehicles. University staff is interested in developing a relationship with a U.S. bus manufacturer, fuel cell developer, and hydrogen storage company.

- CITIC GUOAN Mengguli Corporation (MGL); MGL New Energy Technology Co., Ltd.; Green Power Co.; Tianjin Lintian Double-Cycle Tech. Co.; Suzhou Phylion Battery Co., Ltd.; Tianjin Lishen Battery Joint-Stock Co., Ltd.; and Tongji University are willing and interested in providing cells, modules, and packs for benchmarking in the United States. However, these organizations would want to see a test plan up front and would like to keep their test data out of the public domain.

- The China Electrotechnical Society has 123,000 members. The society is a clearinghouse for electrotechnical research. It conducts studies on battery technology markets for EVs and HEVs. Recently, it completed a preliminary technology study on fuel cells and fuel cell hybrid vehicles for its membership and the Chinese government. It was learned that the Chinese government emphasizes the development of lithium-ion battery technology for vehicular applications. The Chinese government is providing incentives and grants for Chinese-owned and Chinese-operated companies — amounting to as much as 75% of the total cost, which covers most operating and capital expenses. For small companies, these incentives can be upwards of 85%.

- MGL ranks as China's largest manufacturer of the lithium-ion battery cathode material $LiCoO_2$, and it will be the first to market the new cathode materials $LiMn_2O_4$ and $LiCoO_{0.2}Ni_{0.8}O_2$. MGL emphasizes quality control, and has passed the certification of both New and Hi-Tech Enterprise standards and IS09001:2000. With its own synthesis method, MGL claims it produces cathode materials of superior performance and reliability in an environmentally friendly way. Since incorporation, MGL has held a monopoly in China's lithium-ion battery cathode materials market and now is at the forefront of the industry. Besides cathode materials, MGL also produces lithium-ion secondary batteries of high energy density and high capacity for power and energy storage — the capacity ranges from several ampere-hours to several hundred ampere-hours. As China's first power battery manufacturer, MGL leads in marketing high-capacity lithium-ion secondary batteries, which are used in the Beijing Municipality's trial electric bus fleet.

- Tianjin Institute of Power Sources is one of the two national laboratories involved in battery testing and evaluation activities and programs. This testing center of chemical and physical power sources of the Ministry of Information Industry of China was established in 1985. It is considered the largest, most comprehensive, most authoritative, independent quality-testing center for chemical and physical power sources.

- Tianjin Lishen Battery Joint-Stock Co., Ltd., was established in 1998. It has a capitalization of 600 million Ren Min Bi (RMB) ($80.00 million), and a total investment of 1.5 billion RMB ($200.00 million). The production of lithium cells is completely automatic — representing the most automated production line for lithium-ion batteries in China. The production equipment is imported from Japan.

- At its School of Automotive Engineering, Tongji University has world-class facilities to integrate advanced batteries and fuel cells in vehicles and to conduct basic and applied research for the automotive industry. These testing capabilities cover research, testing, and evaluation. The school is collaborating research with lithium battery development companies, fuel cell development companies, and domestic and foreign automobile companies.

- Suzhou Phylion Battery Co., Ltd., is a battery technology corporation set up by Legend Capital Co., Ltd.; the Institute of Physics of the Chinese Academy of Sciences; and Chengdu Diao Group. Suzhou Phylion Battery Co., Ltd., has 82 million RMB ($10.93 million) and a staff of more than 400. The company specializes in manufacturing and selling lithium-ion cells with high capacity and current. Its technology is primarily used in defense, electric bicycles, lighting, portable electronics, medical equipment, and battery-operated tools.

- The General Research Institute for Nonferrous Metals (GRINM), established in 1952, is the largest research and development (R&D) institution in the field of nonferrous metals industry in China. GRINM is conducting basic research on the materials needs and requirements for high-energy and high-power lithium-ion battery technology. GRINM has focused on nanotechnology and $LiMn_2O_4$ materials for the cathode, graphite for the anode, and PC+DC+DMC+1m Li P F6 liquid electrolyte and polypropylene/ polyethylene/polypropylene separator for the development of a lithium-ion battery cell. GRINM developed all materials in-house except for the separator, which GRINM imports from Japan and the United States.

- The production and manufacturing of lithium-ion batteries has expanded enormously in the past two to three years. These batteries are widely used in consumer electronics devices, such as cellular phones, camcorders, and portable computers. This market is growing fast and is second only to that of information technology. At companies we visited, we saw batteries manufactured by a wide variety of processes — from manual production to full automation. Labor cost also plays a significant role in manufacturing lithium-ion batteries. Currently, China has between 275,000 and 325,000 workers in the battery industry. Labor costs in China are very low compared with those in Japan and western countries. Some 435 batteries companies in China are producing batteries. In 2006, their total output was 78.7 billion Yuan.

- Western and Japanese companies are setting up joint ventures and/or partnerships with Chinese battery companies, taking advantage of widespread incentives available to Chinese companies. Chinese companies receive more incentives in producing batteries for export. Today, Chinese companies are providing batteries for electronic and portable applications worldwide. Because the initial investment to produce lithium-ion batteries is very high, producing them in China makes sense for Japanese and western companies.

- The rechargeable lithium battery is a new technology in the energy field supported greatly by the Chinese government. Since the initiation of China's "863 Program" in 1987, the Ministry of Science and Technology has organized the research and development of the key materials and technologies for NiMH and lithium-ion batteries. These batteries are produced on a large scale, particularly for export.

- In its new five-year plan (2006–2010), the Chinese government outlines steps to boost efficiency and reduce pollution. A number of clear targets for increasing energy efficiency are set (e.g., to increase total energy efficiency by 20% and to achieve an energy mix of at least 20% renewable energy by 2020). The Chinese government is also introducing clear policy standards:

  1. Starting April 1, 2006, buyers of new, large cars paid 20% more sales tax than those of new, small cars, and buyers of even smaller cars paid 1% less in sales tax.

  2. In 2006, parking fees in central Beijing were doubled.

  3. The gasoline price for consumers increased by about 20% during 2006.

  4. In December 2005, tighter vehicle standards were approved.

On the whole, the PRC is making vast progress in manufacturing lithium-ion battery technology. The government has a national program in place to attract foreign companies to set up joint ventures and/or partnerships with Chinese companies. The Chinese government offers large incentives to Chinese companies that produce batteries for export. The Chinese government also gives Chinese-owned companies additional incentives to conduct research and provides capital for manufacturing lithium-ion batteries for all applications.

1 INTRODUCTION

Argonne National Laboratory prepared this report, under the sponsorship of the Office of Vehicle Technologies (OVT) of the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy, for the Vehicles Technologies Team. The information in the report is based on the author's visit to Beijing; Tianjin; and Shanghai, China, to meet with representatives from several organizations (listed in Appendix A) developing and manufacturing lithium-ion battery technology for cell phones and electronics, electric bikes, and electric and hybrid vehicle applications. The purpose of the visit was to assess the status of lithium-ion battery technology in China and to determine if lithium-ion batteries produced in China are available for benchmarking in the United States. With benchmarking, DOE and the U.S. battery development industry would be able to understand the status of the battery technology, which would enable the industry to formulate a long-term research and development program. This report also describes the state of lithium-ion battery technology in the United States, provides information on joint ventures, and includes information on government incentives and policies in the Peoples Republic of China (PRC).

1.1 SCOPE OF THE STUDY AND OBJECTIVES

The scope of this study is (1) to determine the state of the art and current production of lithium-ion batteries in China and (2) to develop recommendations for DOE with respect to battery benchmarking and testing of candidate batteries for use in hybrid and plug-in hybrid vehicles. China is the largest country in the world, and its economy is growing rapidly. Because of the demand for world oil supplies, the United States is interested in the capabilities of Chinese manufacturers of motor vehicles to produce and use state-of-the-art, energy-efficient vehicles. Although there are significant issues of competitive concern, there are also reasons to hope that multiple nations will have the ability to produce high-quality, interchangeable battery packs for future plug-in hybrid vehicles. The Chinese government is developing its industry and universities to carry out the research and development (R&D) in lithium-ion battery technology for portable and electric vehicle applications. An estimated 400 organizations in China are involved in battery development or manufacturing; however, manufacturers of lithium-ion batteries represent an unknown fraction of this total.

Some U.S. and Chinese companies have begun to develop joint relationships to conduct R&D and manufacturing of advanced vehicle technologies. The study described in this report on Chinese lithium-ion battery technology could help U.S. companies focus on technologies for which the United States has a competitive advantage. By properly selecting the best Chinese batteries for possible follow-up benchmarking and testing, this study has the potential to strengthen both U.S. and Chinese programs by avoiding undesirable duplication of effort, helping both nations to focus on their strengths with respect to the manufacturing and development of lithium-ion batteries.

Further, DOE's OVT Program always strives to determine the best technologies available for potential use by U.S. automobile manufactures and to build the capability of domestic manufacturers to produce competitive or superior technologies. Similarly, the Energy Storage effort within OVT — through battery testing and benchmarking of Japanese batteries — has also provided U.S. manufacturers and customers with a degree of assurance about the reliability of battery technologies. In the process, the Energy Storage effort has helped provide domestic manufacturers information needed to support internal decisions to proceed with programs to develop hybrid and plug-in hybrid vehicles. Greater confidence in the ultimate marketability of hybrid powertrain technologies will help ensure the success of the vehicle development program.

The purpose of this study is consistent with past efforts of the U.S. Advanced Battery Consortia (USABC) and FreedomCAR Partnership for the development of battery technologies — which will benefit from the results of this study. It provides a lithium-ion battery technology assessment specific to China, as well as information on contacts with key organizations and manufacturers. As DOE embarks on a new “Plug-In Hybrid Initiative,” this study identifies lithium-ion battery technologies compatible with powertrain technologies being developed in the United States, increasing the likelihood that such powertrains can help reduce the rate of growth in oil consumption.

1.2 METHODOLOGY AND APPROACH

Five battery research and testing organizations, one battery technology society, and five companies conducting research and development of lithium-ion battery technology (as well as manufacturing lithium-ion batteries) were visited in the PRC. During this visit, 28 interviews were conducted (Appendix A). A presentation was made to each of these organizations on the status of lithium-ion battery technology for electric, hybrid, and plug-in hybrid applications in the United States (see Appendix B). The interviewed individuals included those from industry, government laboratories, and academia. Individuals interviewed from industry included representatives from materials suppliers and representatives from battery manufacturers serving in technology development, management, and marketing positions. Each interviewee received a list of questions in advance that served as a guide to the interview process. (Appendix C lists the questions used to guide the personal interviews.) Interviews did not always follow the sequence of the listed questions. The interviews were conducted in a relaxed setting and in a conversational manner, which helped the experts to focus on what they considered to be the most important factors influencing the development of lithium-ion battery technology and the decisions of manufacturers about the production of lithium-ion batteries. Responses from those interviewed helped Argonne identify and analyze developments in lithium-ion battery technology in the PRC and to obtain information about cost estimates and manufacturing capabilities.

The initial contacts in the United States were made by attending advanced battery technologies meetings, seminars, and conferences, such as the Advanced Automotive Battery Conference 2007. The contacts and conferences provided information on developments in lithium-ion battery technology in the United States, Europe, and Asia. These conferences were extremely useful in understanding the status of lithium-ion batteries, in comparison with activities related to lithium-ion batteries in the PRC.

1.2.1 Overview and Discussion

Lithium-ion batteries offer higher power and energy per unit weight and volume, as well as a better charge efficiency, than NiMH batteries. These attributes allowed them to capture a major part of the portable rechargeable battery market within only a few years of their introduction and to generate global sales estimated at $5 billion in 2006. Nevertheless, the tolerance of lithium-ion technology to abuse is still questionable, its reliability for automotive applications is not proven, and currently, its cost is higher than that of NiMH. Over the last five years, most automakers have started to evaluate the suitability of lithium-ion batteries for hybrid electric vehicle (HEV) applications, and some have even embarked on significant in-house lithium-ion battery development projects. In the future, the lithium-ion battery is likely to become the battery of choice for most hybrid applications. When exactly this will happen for each of the hybrid vehicles is a question that automakers, battery developers, their supply chains, and the many industry stakeholders and observers are struggling to answer.

1.2.2 Lithium-Ion Battery Technology — Technology Discussion

Mass-manufacturers of lithium-ion cells for consumer products are now engaged in the development of lithium-ion chemistries for HEV and plug-in hybrid electric vehicle (PHEV) applications, with possible commercialization as early as 2012. The major impediment to developing lithium-ion batteries for PHEVs appears to be that the requirements for PHEV batteries are insufficiently defined at this time. The apparent interest in PHEVs by General Motors Corporation (GM) might stimulate efforts to develop lithium-ion technology for PHEV applications. Several companies in Europe and Japan have been developing medium- and high-energy lithium-ion technologies, some of them based on advanced materials, chemistries, and/or manufacturing techniques. Their strategy is to pursue limited-volume applications and markets that may be emerging, especially for small battery-powered electric vehicles (EVs); electric bikes; and, more recently, PHEVs. Several of these companies hold the view that lithium-ion-powered PHEVs and small battery-powered electric vehicles will be able to match the life-cycle cost-competitiveness of conventional vehicles in urban fleet applications, and a few have established cell-production capacities for hundreds to a few thousand of 10–25-kWh batteries per year, which may be sufficient for demonstration fleets.

As the lightest metal and most electronegative element, lithium is the most attractive negative electrode material for high-energy batteries. However, its high reactivity with water and with the solvents used in organic battery electrolytes has prevented its use in rechargeable batteries until two important discoveries were made about 15 years ago: lithium can be inserted (“intercalated”) electrochemically in carbon “host” materials, and a protective layer forms at the interface of the lithium-containing carbon with the organic electrolyte solvent when a cell is charged for the first time. Remarkably, this complex solid-electrolyte interface (SEI) layer prevents further attack of the electrolyte by lithium but allows the passage of lithium ions during charge-discharge cycling. The host material forming the negative electrode in lithium-ion cells is made from special grades of graphite and/or coke. Mixed with binders, these carbons are deposited on thin copper sheets that serve as conducting supports. A variety of materials can be paired with carbon-based negatives in battery cells by using organic electrolytes. Mixed with carbon for increased conductivity and with binders, these materials are deposited on thin aluminum sheets as conducting supports. Currently established cathode electrode materials are listed in Table 1 and are reviewed below in the context of current lithium-ion battery technology.

$LiCoO_2$: Lithiated cobalt oxide is the main component of the positive electrodes in lithium-ion cells produced on a very large scale for consumer product applications. It has good storage capacity for lithium ions, adequate chemical stability, and good electrochemical reversibility. However, it is relatively more expensive per kilowatt-hour of storage capacity than other oxides and is therefore not a good candidate for automotive applications of lithium-ion batteries that are under severe cost constraints.

$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$: Commonly termed NCA, this lithiated mixed oxide of nickel, cobalt, and aluminum has become accepted for batteries in prototypical HEV, full performance battery electric vehicle, and the PHEV. It approaches the favorable characteristics of $LiCoO_2$ at a lower per-kilowatt-hour cost.

$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$: Often termed NCM, this lithiated mixed oxide of nickel, cobalt, and manganese is potentially less expensive than NCA. It can be charged to two cell voltage levels. At the higher voltage (e.g., 4.1–4.2 V), NCM yields excellent storage capacity and relatively low per-kilowatt-hour cost but tends to degrade through the dissolution of manganese; at lower voltage, its capacity is substantially less and the per-kilowatt-hour cost is higher, but stability appears adequate.

TABLE 1 Cathode Electrode Materials

Active Material Chemical Formula (discharged state)	Storage Capacity (mA•h/g)	Normal Voltage (V)	Wh/kg	Wh/L	Material Cost Range ($/kg)	($/kWh)
$LiCoO_2$	145	4.0	602	3,073	30–40	57–75
$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$	160	3.8	742	3,784	28–30	50–55
$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$	120	3.85	588	2,912	22–25	30–55
$LiMnO_2$	100	4.05	480	2,065	8–10	20–25
$LiFePO_4$	150	3.34	549	1,976	16–20	25–35

Notes:

- Lower potential can provide greater stability in electrolyte
- Cobalt oxide is most widely used in consumer cells but recently too expensive; $LiMn_{1/3}Co_{1/3}Ni_{1/3}O_2$ newer than $LiNiCoO_2$
- Mn_2O_4 around for many years – not competitive for consumer – good for high power
- $LiFePO_4$ – very new – energy density too low for consumer electronics – safe on overcharge; however, need electronics to prevent low voltage

$LiMnO_2$: Lithium manganese spinel, denoted LMS, is more stable than cobalt oxide and nickel oxide-based positives in lithium-ion cells because the spinel crystal structure is inherently more stable and has no or little excess lithium ions in the fully-charged state. Thus, it provides very little lithium for undesirable lithium metal deposition on the negative electrode in overcharge. Also, the threshold of thermal decomposition of the charged (lithium-depleted) material is at a considerably higher temperature than that of other positive electrode materials. Despite its lower specific capacity, the expected substantially lower per-kilowatt-hour cost will make LMS attractive, if the efforts to stabilize the material against electrochemical dissolution of its manganese content are successful.

$LiFePO_4$: Lithiated iron phosphate (olivine), denoted LFP, is now being used successfully as a potentially lower-cost positive electrode material. Because of its lower electrochemical potential, LFP is less likely to oxidize the electrolyte solvent and thus is more stable, especially at elevated temperatures. Doping is used to increase the conductivity and stability of this promising material.

The electrolyte used in lithium-ion battery cells is a solution of a fluorinated lithium salt (typically $LiPF_6$) in an organic solvent, enabling current transport by lithium ions. Separators are usually microporous membranes made of polyethylene or polypropylene. Because of the low conductivity of organic electrolytes, adequate cell and battery power can be realized only with electrodes and separators that are much thinner than those used in aqueous-electrolyte batteries. The need for thin electrodes has made spiral winding of positive electrode-separator negative electrode composites the preferred method for the fabrication of lithium-ion cells, but flat cell configurations packaged in soft plastic (often metallized) enclosures are now gaining acceptance.

1.3 LITHIUM-ION BATTERY THERMAL MANAGEMENT

Battery thermal management is critical in achieving adequate performance and extending life of batteries in electric and hybrid vehicles under real driving conditions. Designing a battery thermal management system for given HEV/PHEV battery specifications starts with answering a sequence of questions:

- How much heat must be removed from a pack or a cell?
- What are the allowable temperature maximum and difference?
- What kind of heat transfer fluid is needed?
- Is active cooling required?
- How much would the added cost be for the system?

To find a high-performance and cost-effective cooling system, it is necessary to evaluate the system thermal response and its sensitivity as a function of controllable system parameters.

Battery temperature affects battery performance and life. Therefore, battery thermal management is a critical element for achieving the desired performance and calendar life for battery packs in HEVs. Automakers and their suppliers are paying increased attention to battery thermal management to ensure that warranty costs for battery replacement are reasonable. The battery in an HEV experiences a demanding thermal environment and may need to be heated during cold-weather operation and cooled during extended use and during warm-weather operation. A uniform temperature should be maintained among the battery's cells because cell-to-cell temperature variability leads to imbalances and reduced performance and it potentially reduces calendar life.

In the thermal design process, researchers should consider the cell-to-cell variability in a multi-cell pack, which could lead to different battery electrical and thermal behavior. There is also variability in the mechanical design and method for heating or cooling each cell. Also during the thermal design process, researchers should consider the impact of various design parameters, such as state of charge (SOC), internal resistance, current amplitude, heat-generation rate, fluid flow rate, cooling/heating fluid temperature, and various geometrical variations. The goals of a battery thermal management system are to keep the battery below a certain temperature and to minimize the temperature variation in the pack while using a minimum amount of energy.

1.4 AIR COOLING VERSUS LIQUID COOLING

The choice of a heat-transfer medium has a significant impact on the performance and cost of the battery thermal-management system. The heat-transfer medium could be air, liquid, a phase-change material, or any combination of these media. Heat transfer with air is achieved by directing/blowing the air across the modules. However, heat transfer with liquid could be achieved by using discrete tubing around each module, using a jacket around the module, submerging modules in a dielectric fluid for direct contact, or placing the modules on a liquid heated/cooled plate (heat sink). If the liquid is not in direct contact with modules, such as in tubes or jackets, the heat-transfer medium could be water/glycol or even refrigerants, which are common automotive fluids. If modules are submerged in the heat-transfer liquid, the liquid must be dielectric, such as silicon-based or mineral oils, to avoid any electrical shorts.

Using the air as the heat-transfer medium may be the simplest approach, but it may not be as effective as heat transfer by liquid. The rate of heat transfer between the walls of the module and the heat-transfer fluid depends on the thermal conductivity, viscosity, density, and velocity of the fluid. For the same flow rate, the heat-transfer rate for most practical direct-contact liquids (such as oil) is much higher than that with air because of a thinner boundary layer and a higher fluid thermal conductivity. However, because of oil's higher viscosity and associated higher pumping power, a lower flow rate is usually used, making the heat-transfer coefficient of oil only 1.5–3 times higher than that of air. Indirect-contact heat-transfer liquids (such as water or water/glycol solutions) generally have a lower viscosity and a higher thermal conductivity than most oils, resulting in higher heat-transfer coefficients. However, because the heat must be conducted through walls of the jacket/container or fins, the effectiveness of indirect contact decreases.

1.5 ACTIVE VERSUS PASSIVE SYSTEMS

Because of cost, mass, and space considerations and their use in mild climates, battery packs in early vehicles — particularly EVs — did not use heating or cooling units and depended on the blowing of ambient air for the rejection of heat from the batteries. Early prototype HEVs also used passive ambient air-cooling. Current production HEVs (Honda Insight and Toyota Prius) use cabin air for cooling/heating of the pack. Although the ambient air is heated and cooled by the vehicle's air-conditioning or heating system, it is still considered to be a passive system. For passive systems, the ambient air must have a mild temperature (10–35°C) for the thermal management to work; otherwise, the performance of the pack can suffer in very cold or very hot conditions. Outside of these conditions, active components (such as evaporators, heating cores, engine coolant, or even electric and fuel-fired heaters) are needed.

1.6 COOLING-ONLY SYSTEMS VERSUS COOLING AND HEATING SYSTEMS

Electric vehicles were initially aimed for the mild to warm climate of California. Battery performance is generally better at higher temperature; however, battery life can decrease with higher temperature. Therefore, batteries in those EVs needed to be cooled only, and there was no need for too much heating. At cold temperatures (below –10°C), the energy/power capability of most batteries diminishes, and electric vehicle (EV) and HEV performance diminishes as well. Heating systems have been used for EVs operating in colder climates. For EVs, there is no engine to aid in heating the battery pack, so the heat rejected from motor and power electronics and electricity from the battery could be used for heating; otherwise, a fuel-fired heater could be considered. For HEVs, the heat from the engine could be used, but it would take some time (more than 5 min) for the engine to start warming the batteries. Because power from the battery is needed much sooner, self-heating battery technology could be an option. Cooling the batteries is a less-challenging task than heating because the vehicle's air-conditioning/refrigerant system or engine coolant could be used. Energy use, however, increases with the use of refrigeration, which is contrary to the HEV goal of improving fuel economy.

1.7 SERIES VERSUS PARALLEL AIR DISTRIBUTION

There are two methods for distributing air to a pack for cooling and/or heating. The first method is *series* cooling, in which air enters from one end of the pack and leaves from the other, exposing the same amount of air to several modules. The second method is *parallel* cooling, in which the same total airflow is split into equal portions, and each portion flows over a single module. Depending on the size and geometry of the modules, a series-parallel combination could be configured. Generally, *parallel* airflow provides a more even temperature distribution among the modules in a pack. The packs in GM's EV1, Toyota's RAV4-EV, Honda's Insight HEV, and Toyota's Prius (Japanese version) all have either series or series-parallel air distribution. The Toyota Prius (North American version) uses a pure parallel air distribution system or even-temperature distribution. In parallel flow design, distributing airflow uniformly to a large battery pack requires a careful design of the air manifold.

1.8 THERMAL MANAGEMENT FOR VALVE-REGULATED LEAD-ACID, NiMH, AND LITHIUM-ION BATTERIES

The relative need for the thermal management of each of the valve-regulated lead-acid (VRLA), nickel metal hydride (NiMH), and lithium-ion batteries depends on the heat-generation rate from each type of battery, its energy efficiency, and the sensitivity of performance to temperature. From Table 2, it can be seen that NiMH batteries generate the most heat at high temperatures (>40°C) and are the least efficient. At room temperature, NiMH generates less heat than VRLA and lithium-ion batteries. The performance of a NiMH battery is more sensitive to temperature than VRLA and lithium-ion batteries. Therefore, NiMH batteries need a more involved battery management control. This is also evident from various efforts to use the more effective liquid cooling for NiMH batteries. The concerns for lithium-ion packs are safety and their relatively poor performance at very cold temperatures. Because lithium-ion batteries can deliver much more power and thus more heat for the same volume than either VRLA or NiMH, heat removal must be efficient. Thermal management also depends on the type of vehicle and the location of the pack. For EVs and series HEVs, the pack is generally large, and its thermal management system may need to be more elaborate — possibly incorporating liquid cooling (particularly for NiMH). However, for parallel HEVs, the pack is generally smaller, and the thermal control could be achieved by a simpler air cooling/heating design, especially for lithium-ion and VRLA batteries.

TABLE 2 Heat Generation from Typical HEV/EV Modules Using NREL's Calorimeter

		Heat Generation W/Cell		
Battery Type	Cycle	0°C	22–25°C	40–50°C
VRLA, 16.5 A•h	C/1 Discharge, 100% to 0% SoC[a]	1.21	1.28	0.4
VRLA, 16.5 A•h	5C Discharge, 100% to 0% SoC	16.07	14.02	11.17
NiMH, 20 A•h	C/1 Discharge, 70% to 35% SoC	-	1.19	1.11
NiMH, 20 A•h	5C Discharge, 70% to 35% SoC	-	22.79	25.27
Lithium-Ion, 6 A•h	C/1 Discharge, 80% to 50% SoC	0.6	0.04	-0.18
Lithium-Ion, 6 A•h	5C Discharge, 80% to 50% SoC	12.07	3.50	1.22

[a] SOC = state of charge.

A well-designed thermal management system is required to regulate EV and HEV battery pack temperatures evenly, keeping them within the desired operating range. Production HEVs require an active heating/cooling battery temperature monitoring system to allow them to operate in hot and cold climates. Proper thermal design of a module has a positive impact on the overall management and behavior of the pack. A thermal management system using air as the heat-transfer medium is less complicated, although also less effective, than a system using liquid cooling/heating. Generally, for parallel HEVs, an air thermal management system is adequate, whereas for EVs and series HEVs, liquid-based systems may be required for optimum thermal performance. The NiMH batteries require a more elaborate thermal management system than lithium-ion and VRLA batteries. Lithium-ion batteries also need a good thermal management system because of safety and concerns about low-temperature performance. The location of the battery pack may also have a strong impact on the type of battery thermal management and whether the pack should be air-cooled or liquid-cooled.

1.9 HEAT GENERATION AND HEAT CAPACITY

The magnitude of the overall heat-generation rate from a battery pack under load dictates the size and design of the cooling system. The heat generation (due to electrochemical enthalpy change and electrical resistive heating) depends on the chemistry type, construction, temperature, state of charge, and charge/discharge profile. At the National Renewable Energy Laboratory (NREL), a custom-built calorimeter to measure the heat generation from cells/modules with various cycles, states of charge, and temperatures is used. Table 2 shows some typical results for various batteries from an experiment by NREL. These and other data show that, for the same current draw, a NiMH battery generates more heat than VRLA or lithium-ion batteries at elevated temperatures (>40°C). Heat generation from VRLA and lithium-ion batteries is roughly the same for similar currents. At room temperature, less heat is generated for NiMH for the same current, but NiMH is not as energy-efficient. Generally, as temperature decreases, more heat is generated because of an increase in resistance in the cells. As the discharge rate increases, more heat is generated. Under certain conditions, the battery electrochemical reaction could be endothermic, as shown in Table 2 for lithium-ion batteries at a C/1 discharge rate at 50°C.

1.10 LITHIUM-BASED BATTERIES: ADVANTAGES AND CHALLENGES

A key advantage of lithium-based batteries is the high cell voltage, the direct result of the highly negative potential of lithium. With currently used mixed-oxide positives, the lithium-ion cell operating voltage range is approximately 2.75–4.2 V. The nominal (average) discharge voltage is about 3.6 V, and most of the usable cell capacity is delivered between 4.0 and 3.5 V. With iron phosphate positives, the nominal cell voltage is about 3.4 V. The high cell voltage is the fundamental reason for the high specific energy of lithium-ion cells and batteries. The high cell voltage also results in a smaller number of cells for a battery of given voltage, for reduced fabrication costs and increased reliability. A second basic advantage of the lithium-ion electrochemistry is based on the small size of lithium, which permits reversible electrochemical intercalation of lithium atoms into carbon-based negative electrodes with little structural stress and strain. Similarly, the very small lithium ion is readily and reversibly incorporated into a variety of host oxides that form the positive electrode. These characteristics are responsible for maintaining the integrity of both electrodes during charge-discharge cycling, a key requirement for long cycle life — especially in deep-discharge cycling. As discussed further below, key technology advantages of lithium-ion batteries are high power density and energy efficiency as a result of thin-cell construction and low self-discharge rate.

The main challenges encountered in the development of lithium-ion technologies for practical applications are also due to the highly negative potential of lithium. It is a powerful driving force not only for the effectiveness of lithium as a negative electrode but also for its chemical reactivity within the cell. Only the formation of an SEI prevents continued, uncontrolled reaction of lithium with the electrolyte solvent and enables the controlled discharge and recharge of lithium-ion cells and batteries. Once formed as a protective thin layer, the SEI must be stabilized chemically and kept from growing thicker because of the associated irreversible declines of cell capacity (through the loss of lithium) and of peak power (through growth of cell resistance). Choosing proper electrolyte solvents and additives and keeping cell temperatures below approximately 45–50°C are very important for stabilizing the SEI and achieving practical calendar and cycle life.

Another key challenge is the sensitivity of lithium-ion cells to overcharge that can result in chemical decomposition of positive electrode materials and the electrolyte and/or in the deposition of metallic lithium at the negative electrode. These processes damage the cell and can result in hazardous conditions, including gassing and release of flammable electrolyte solvent vapors, if the cell safety seal is breached as a result of excessive gas pressure. To avoid overcharge, lithium-ion batteries require accurate voltage control for every cell, unlike NiMH and other aqueous electrolyte batteries that can tolerate significant amounts and rates of overcharge. Accurate and reliable control of cell voltage and temperature is thus critical requirements for achieving long life and adequate safety of lithium-ion batteries for all uses, but especially so for automotive applications, which demand a very long battery life and high levels of safety.

2 LITHIUM-ION BATTERIES: STATE OF THE ART

2.1 PERFORMANCE AND LIFE

For more than a decade, prospective manufacturers have been developing lithium-ion batteries for electric vehicles. A number of these efforts were terminated when the initiatives to introduce electric vehicles were abandoned earlier in this decade. However, some programs continued and resulted in the development of high- or medium-energy/medium-power lithium-ion technologies. Although none of the programs have generated commercially available batteries as yet, a few have resulted in the low-volume production of cells and in-vehicle evaluation of prototype batteries. Key characteristics of these technologies are summarized in Table 3.

Table 3 indicates that current designs of high-energy cells achieve energy and power density levels of at least 150 Wh/kg and 650 W/kg. Batteries of 20–30 kWh using such cells can attain energy densities of around 100 kWh/kg and power densities of 250–350 W/kg or above, which is sufficient for small or even full-performance electric applications at acceptable battery weights. Also, medium-power lithium-ion cells in the appropriate size range enable construction

TABLE 3 Status of Lithium-Ion High-Energy/Medium-Power Cell and Battery Technologies

	Manufacturer				
Component	JCS	GAIA	LitCEL	Lamilion	Kokam
Cell	VL 45E/41M	HE/HP Series	EV Type	EV Type	HE/HP
Voltage (V)	3.6	3.6	3.85	3.6	3.7
Capacity (A•h)	45/41	60/45	50/33	13	100/40
Energy Density (Wh/kg)	150/136	150/105	136/142	~150	163/135
Energy Density (Wh/L)	314/286	380/284	270	270	340/285
Peak Power Density (W/kg)	664/794	900/1,500	1,500	1,300	~700/~1250
Power/Energy Ratio (L/h)	4.4/5.8	~6/~14	7.7	8.7	~4.3/~9
Cycle Life (Cyc. @% DOD)	~3,200 (80)	~1,000 (70)	~1,000	~1,400 (100)	~3,000 (80)
Calendar Life (years at RT)	~12	–	–	~10	~10
Development Status	LP	LP	LP	LP	LP
Battery (Applications)	EV/PHEV	EV/PHEV	EV/PHEV	Small EV	EV/PHEV
Storage Capacity (kWh)	~24/15	22/8.1	20/7.6	9.2	~30/~5
Energy Density (Wh/kg)	90/94	115/74	118/117	~70	~110/~100
Energy Density (Wh/L)	145/80	165/130	194	–	–
Peak Power (kW)	55/87	50/80	155/60	62	130/47
Peak Power Density (W/kg)	210/540	~250/730	912/917	~400	~490/~940
Power/Energy Ratio (1/h)	2.3/4.6~2.2/~10	7.7/7.8	6.7	~4.3/~9.4	
Weight (kg)	265/160	200/110	170/65	150	265/~50
Development Status	LP;VE	LP;VE	LP; VE	LP; VE	LP

of 7.5–15-kWh batteries with energy densities above 70 Wh/kg and power densities in the 500–900 W/kg range, values that can readily meet the performance requirements of PHEV batteries.

Table 3 also includes data on cycle and calendar lives, which are two of the remaining concerns about the readiness of lithium-ion batteries for vehicle applications. The more than 3,000 deep cycles achieved by Saft (a "world specialist in the design and manufacture of high-tech batteries for industry"), and also claimed by Kokam, indicate that large lithium-ion cells have the potential for very long cycle life. The calendar life of state-of-the-art, high-energy lithium-ion technology is also much improved over the values of 2–4 years that were typical five years ago.

Table 4 presents performance and life data for high-power/medium-energy lithium-ion cell and battery technologies for HEV applications. This table shows a promising lithium-ion high-power technology in a smaller cell size that has been commercialized by A123Systems for power tool applications. The basic technology is expected to be developed into larger cell sizes of higher power density for HEVs, an application for which it is well suited because of the safety advantages of iron phosphate-based positives.

TABLE 4 Status of Lithium-Ion High-Power/Medium-Energy Cell and Battery Technologies

	Manufacturer					
Component	JCS	Matsushita	HitachiVE	Kokam	GAIA	A123Systems
Cell	VL7P	Gen 2	UHP	HP	MI 26650	–
Voltage (V)	3.6	3.6	3.4	3.7	3.6	3.3
Capacity (A•h)	7	7	5.5	7.2	7.5	2.3
Energy Density (Wh/kg)	67	92	–	114	84	110
Power Density (W/kg)	1,800	3,400	–	2,600	1,500	1,950
Power/Energy Ratio (l/h)	27	37	–	23	18	20
Power Density (W/L)	3,525	–	–	4,900	3,750	4,200
Cycle Life (shallow cycles)	~400k	–	~750k	–	–	~240k
Cycle Life (cycles/DOD)	–	~1,000	–	~3,000/80	1,000/60	7,000/100
Calendar Life (years@RT)	~20	–	–	~10	–	~15
Development Status	LP	–	–	LP	LP	CP
Battery (Application)	HEV	HEV	HEV	HEV	HEV	PT
Storage Capacity (kWh)	2	3	1	2.6	2	–
Peak Power (kW)	50	90	47	52	25	2.1
Peak Power Dens. (W/kg)	1,110	2,100	1,900	1,850	–	–
Power Density (W/L)	1,110	--	2,100	–	–	2,200
Energy Density (Wh/kg)	44	70	42	93	–	–
Power/Energy Ratio (1/h)	25	30	45	20	12.5	–
Weight (kg)	45	43	22.5	28	–	–
Development Status	PP	D	PP	LP	–	–

Even smaller lithium-ion cells of the type used in consumer electronic products are being used for developmental PHEVs and full performance battery electric vehicles (FPBEVs) in the form of batteries that consist of several thousand cells connected in parallel and in series. This approach takes advantage of lithium-ion cells that are available now, since they are being produced in very large numbers and sold at competitive prices for laptop computers. However, it raises questions regarding the reliability, safety, and ultimately achievable cost of "small-cell" batteries.

The calendar life of high-power lithium-ion battery cells is expected to depend on temperature much in the same way as high-energy cell designs, because several of the high-power cell technologies use the same basic chemistry as larger cells and thus are subject to the similar degradation processes.

Table 5 provides information on lithium-ion battery developers and on types of cathodes, anodes, packaging, cell structures, and cell shapes used in battery developments.

As with high-energy lithium-ion technologies for battery-powered electric vehicles and PHEV applications, a key technical issue is whether developers can meet the very high levels of safety required for vehicles operated on public roads.

2.2 COST

The current cost of lithium-ion HEV batteries made with early pilot equipment is around $2,000/kWh. If the current designs were brought to volume production, it is anticipated that the cost would drop to approximately $1,000/kWh.

TABLE 5 Developers of Lithium-Ion Technology Cells for HEV Applications

Company	Cathode	Anode	Packaging	Structure	Shape
Toyota	NCA	graphite	metal	spiral	prismatic
Panasonic	NMC	blend	metal	spiral	prismatic
JCS	NCA	graphite	metal	spiral	cylindrical
Hitachi	NMC/LMO	hard carbon	metal	spiral	cylindrical
NEC-Lamilin	LMO/NCA	hard carbon	pouch	stacked	prismatic
Sanyo	NMC/LMO	blend	metal	spiral	cylindrical
GS Yuasa	LMO/NCA	hard carbon	metal	spiral	prismatic
A123 Systems	LFPO	graphite	metal	spiral	cylindrical
LG Chem.	LMO	hard carbon	pouch	stacked	prismatic
Samsung	LMo/NMC	graphite	metal	spiral	cylindrical
SK Corp.	LMO	graphite	pouch	spiral	prismatic
EnerDel	LMO	LTO	pouch	spiral	prismatic
AltairNano	NMC/LCO	LTO	pouch	stacked	prismatic

The cost calculation procedure for a lithium-ion battery module using 10-A•h $LiMn_2O_4$ HEV cells is illustrated in the following discussion. The cell's material cost is estimated at $9.93, with the key cost drivers classified by order of importance as follows: (1) separator, (2) electrolyte, (3) $LiMn_2O_4$, (4) graphite, and (5) copper foil — these five factors account for 75% of the cell's material cost.

Assuming that materials before yield losses represent 65% of the cost of goods (considerably less than that for NiMH because of the lower yield and higher depreciation for lithium-ion technology), and with a low gross margin of 30%, the calculated cost of a cell is $606/kWh. Further, assuming that the cost of the module per kilowatt-hour is 1.5 times the cost of the cell, and that the pack cost per kilowatt-hour is 1.43 times that of the module, we arrive at a module cost of $1,011 and a pack cost of $1,444/kWh.

The following analysis of the "best-case" scenario is more uncertain than that for the NiMH battery, because:

- The cathode material, $LiMn_2O_4$, is not yet in high-volume production.

- The separator and the electrolyte are the top two items driving the cost of materials. In both cases, the high cost is a result of the difficulty of making these high-purity (electrolyte) and high-dimensional-accuracy (separator) materials, even though the cost of the underlying raw materials is quite moderate.

- Yield is a significant item affecting cost in early years of production; the allowable factor for the yield of materials is attributed as 65%, as compared with 75% in the case of NiMH.

- The cost of electrical management for the module and pack is very high at present. Although reductions in cost will occur, they are difficult to estimate at this point. Under the "best-case" scenario, there will be significant reductions in the cost of materials and in module and pack peripheral costs. Certain advances in materials — possibly including new electrolyte salts, new cathode material, and a less-expensive process to make the separator — may occur. Such innovations, when fully developed and tested, could lower the price of the battery. This may take 5 to 8 years.

In 1994, the cost of 18650 type (rated at 1,100-mA•h) cylindrical consumer lithium-ion cells was over $10 per cell at a high volume. In 2001, the capacity of the cell increased to 1,900-mA•h, and the cost dropped to around $2.00 per cell at the comparable volume, resulting in a drop in cost of $3/Wh for a comparable 1,100-mA•h cell. This is a remarkable improvement in less than seven years. The recent price of this cell — now made in quantities of over 100 million per year — is about $300/kWh. The HEV cell, with its ultra-thin electrodes, uses approximately twice the amount of separator and electrolyte per watt-hour as the consumer cell; this has a significant impact on the cost of materials and manufacturing, which is determined to a large extent by the design of the electrodes.

2.3 LITHIUM-ION BATTERY SAFETY

Battery safety is critical for the success of lithium-ion batteries for HEV, PHEV, and EV applications. Lithium-ion battery safety is tied directly to the avoidance or strict control of those processes in lithium-ion battery cells that, if uncontrolled, can release dangerous amounts of energy, flammable gases, and/or toxic chemicals into the battery environment. These processes include (1) electrochemical overcharging of battery cells and the ensuing reactions of the chemical species formed during overcharge and (2) chemical reactions of the organic electrolyte/solvent with one or both electrodes. Under normal operating conditions of cell voltage and temperature, these processes are either precluded through cell-level voltage control (overcharge) or occur at very low rates that do not constitute safety risks.

Concerns about lithium-ion battery safety thus can be limited to the response of cells and batteries to "abuse," including electrical/electrochemical (shorting, high rate, and extensive overcharging), thermal (heating to temperatures above the cell tolerance limit), and/or mechanical (destruction of physical integrity). Abuse tolerance testing has become part of cell development, as well as battery design and engineering efforts. The degree of tolerance to various abuses is serving as a relative measure of safety and as a guide to the development of adequately safe lithium-ion cells and batteries. The procedures most commonly used in lithium-ion abuse testing were developed with DOE funding under the USABC and FreedomCAR programs and are now widely accepted. Results of systematic abuse testing of small commercial lithium-ion cells following these procedures show that sustained high-rate/high-voltage overcharge and massive shorting of some lithium-ion cell types can cause thermal runaway that is accompanied by cell-internal gas evolution, cell venting, and (if triggered by sparks) burning of vented electrolyte solvent. However, these conditions can be created only if the standard, multiple levels of protection devices (e.g., voltage-sensitive and pressure-driven switches to interrupt current; current-sensitive and temperature-activated fuses; and cell-balancing electronics) are removed.

Although the chemistries of the cells and batteries used in EV and HEV battery technology are similar to the chemistries used in lithium-ion laptop batteries, the cell and battery designs are substantially different. Even more important, batteries for HEV, PHEV, and battery-powered electric vehicle applications have voltage, pressure, and temperature sensors integrated in multiple, independent controls that prevent or terminate unsafe battery conditions of the type that have resulted in some laptop battery fires.

Experience with more than 200 electric and hybrid vehicles equipped with lithium-ion batteries designed for FPBEVs or HEVs and road tested in California, Europe, and Japan over the past five years validates the high level of safety achieved for current lithium-ion technology. No significant safety issues were encountered during these tests.

While lithium-ion technology representing the state of the art of several years ago has proven safe in on-road vehicle testing, R&D is continuing to further enhance battery life and safety, as part of extensive worldwide efforts to advance all aspects of lithium-ion cell and battery technology. Challenges for developing lithium-ion battery technology are costs at initial production volumes, safety, life, and manufacturing reliability.

2.4 LITHIUM-ION BATTERY INDUSTRY IN CHINA

The PRC is the country with the largest population in the world. The PRC has been involved in battery technology developments and manufacturing for several years. The PRC exported the largest number of batteries for telecommunication, computers, cell phones, and other electronic equipment to many countries over the last 10 years. Several hundred companies, both small and large, are involved in development of lead-acid, NiMH, and lithium-ion batteries for these applications. In the past 3 to 4 years, many outside companies have been bringing advanced battery technologies to the PRC and setting up partnerships and/or joint ventures to manufacture batteries for these and other applications (such as electric bikes, EVs, and HEVs) to take advantage of low labor costs in China and incentives provided by the Chinese government. Companies in the PRC are aggressively working toward development of manufacturing processes for the battery export market.

In 2003, the annual mobile phone production capability of the Chinese telecommunication equipment manufacturing industry reached 200 million sets, with an actual annual output of 186 million sets, among which about 120 million sets were exported — that accounts for a quarter of the total global output of mobile phones. Driven by the mobile phone market, the telecommunication equipment manufacturing industry improved its share of the export market. In 2003, Chinese companies produced 334 million batteries just for mobile phones.

Taking advantage of small early markets for lithium-ion battery technology, Chinese companies were involved in developing a large number of advanced batteries in collaboration with foreign companies. Now those companies are developing lithium-ion batteries for electric bikes, EVs, HEVs, and PHEVs. From 2001 to 2004, the number of battery companies in China increased from 455 to 613; accordingly, the number of employees also increased from 140,000 in 2001 to 250,000 in 2004. The total output reached 63.416 billion Yuan ($8.1 billion) in 2004, which is an increase of 52.58% over 2001.

The sales of batteries produced by large-scale companies in the battery industry were 59.82 billion Yuan ($7.65 billion) in 2004, which was an increase of 53% compared with sales in 2003; an increase of 105% compared with sales in 2002; and an increase of 161% compared with sales in 2001. This growth is attributed to the growth of large companies. In the last four years, the debt-to-asset ratio of China's battery industry has been fluctuating between 54 and 59%.

2.5 INTERNATIONAL STANDARDS FOR THE BATTERY INDUSTRY

The International Electrical Commission (IEC) standards are the most commonly used standards by the battery industry for testing and evaluating battery technologies. The standard for testing nickel-cadmium battery is IEC 60285; the standard for testing nickel metal hydride is IEC61436. For the evaluation of lithium-ion batteries, the most commonly used standards are those developed by SANYO or Panasonic. Some companies use IEC standard 61960 to test and evaluate lithium-ion batteries. Also, the IEEE1625 standard is used to determine the improvements in the reliability of lithium-ion batteries. This standard includes the appearance of portable computers, vibrations, environment protection of the battery unit, and assembly.

2.6 INTERNATIONAL MARKET COMPETITION

Along with development of the electronic product market for mobile phones, notebook computers, digital cameras, and portable video cameras, the lithium-ion battery industry is also growing substantially. In 2003, the global output of lithium-ion batteries surpassed 1.3 billion units, with a growth rate of over 60%, while total sales were more than $4 billion. In 2005, the global output of lithium-ion batteries grew again by 48%.

During 2000–2003, the lithium-ion battery industry in China grew rapidly, at an annual rate of over 140%. At present, the lithium-ion battery market in China is 32 million units per month, which is 29% of the global market share. In 2003, the global top 10 manufacturers of lithium-ion batteries held 81% of the global market share. Four Chinese manufacturers are listed in the top 10: BYD Company Limited; Shenzhen BAK Battery Co., Ltd.; Shenzhen B&K Technology Co., Ltd.; and Tianjin Lishen Battery Joint-Stock Co., Ltd. In the future, along with the expansion in production of BYD Company Limited; Shenzhen BAK Battery Co., Ltd.; Shenzhen B&K Technology Co., Ltd.; and Tianjin Lishen Battery Joint-Stock Co., Ltd., the lithium-ion battery industry in China is expected to grow at an annual average rate of more than 30%.

The Korean lithium-ion rechargeable battery industry is keeping pace with the growth of the electronics industry. In 2005, the global market share for Samsung SDI and Samsung LG Chemistry companies' lithium-ion batteries reached 28%. By 2010, China will reportedly surpass Korea in the growth of the lithium-ion battery industry because the cost of the battery is lower than that in Korea or Japan, according to the officials at the Ministry of Science and Technology (MOST). Therefore, the future of the lithium-ion battery industry in China depends on a breakthrough in quality and performance.

The polymer lithium-ion (PLI) battery has become the leader in the Chinese battery industry, since it performs better and has a higher power density than the conventional lithium-ion battery — plus, it is also lighter and thinner. Although the price of the PLI battery is 10–30% higher than the price of the lithium-ion battery, since 1999 the rate at which the market for PLI batteries is growing is still faster than the rate at which the market for lithium-ion batteries is growing. Compared with 1999, the market share of PLI batteries increased by 8% in 2003 and by 10% in 2004. The market share of PLI batteries is increasing in China, Japan, and Korea, a trend similar to the market for lithium-ion batteries. Because of increasing market demand and expansion plans to produce PLI batteries in China, Japan, and Korea, the market share of PLI batteries will continue to increase annually.

Lithium-ion batteries are widely used in various electronic products, such as handsets, laptops, Personal Digital Assistants (PDAs), and digital video. Some electric vehicles also use lithium-ion batteries. In Japan, 57.4% of lithium-ion batteries are used in mobile phones, 31.5% in notebooks, 7.4% in digital videos, and 3.7% in other products. In China, most lithium-ion batteries are used in handsets and cell phones, because laptops and digital videos have not been popularized yet. Lithium-ion batteries have become the mainstream batteries for the laptop and mobile markets.

In China, such manufacturers as BYD Company Limited; Shenzhen BAK Battery Co., Ltd.; Shenzhen B&K Technology Co., Ltd.; and TCL Corporation (and others) hold large shares of the global lithium-ion battery market. However, the capacity and quality of lithium-ion batteries need to be improved. The obstacles to improving lithium-ion battery performance include cathode development, cost, development of a functional additive, and patent protection.

2.7 GROWTH OF LITHIUM-ION BATTERY TECHNOLOGY IN CHINA

In 2003 and 2004, the lithium-ion battery industry in China was booming, and during that time, many companies established new production lines. In 2004, China had about 60 manufacturers of lithium-ion batteries. Market competition has been intense; the total market share of the top 10 manufacturers in 2003–2004 was about 85%, indicating that enterprises find it difficult to compete with large manufacturers.

Along with the rapid growth in the number of lithium-ion battery manufacturers in China, companies like BYD Company Limited; Tianjin Lishen Battery Joint-Stock Co., Ltd.; Shenzhen BAK Battery Co., Ltd.; and Shenzhen B&K Technology Co., Ltd., are also increasing their market share. In 2004, the domestic and overseas markets for lithium-ion batteries were flourishing, the export volume was 189 million units, and sales increased by 16.3%. Because of the rapid increase in domestic demand and the import of 550 million units of lithium-ion batteries, sales increased by 23.4% in 2004. In the future, along with the expanded production by some key enterprises and the continuous growth of portable products such as mobile phones and notebook computers, China’s lithium-ion battery industry could still maintain the annual average growth rate of more than 30%.

2.8 KEY RAW MATERIAL

The rapid growth of the lithium-ion battery industry in China drives the growth of the key raw material industry for lithium-ion batteries. Before 2001, the raw materials for lithium-ion batteries were mainly imported. However, domestic sources now supply separator material, anode material, electrolyte, and cathode material for lithium-ion batteries. At the end of 2003, Gejiu City in Yunnan Province established production lines for lithium cobalt, with an annual production capability of 800 tons. In 2004, the Chinese Academy of Geological Sciences developed a new technique for extracting lithium from salt lakes and established a demonstration-engineering project for a source of salt lake lithium in Baiyin City in Gansu Province. So far, the Chinese Academy of Geological Sciences has produced 600 tons of lithium carbonate. In 2004, key manufacturing equipment for LiNiO was developed to mass-produce it at a production capability of 500 tons per year. China has abundant nickel resources; therefore, establishing LiNiO production lines will alleviate the import situation. Chinese companies will not have to depend on importing anode material for lithium-ion batteries. In early 2004, the production of carbon material for lithium-ion battery anodes surpassed 1,000 tons.

At present, China has a relatively well-developed lithium-ion battery manufacturer base. Manufacturers such as BYD Company Limited; Shenzhen BAK Battery Co., Ltd.; and Shenzhen B&K Technology Co., Ltd., enjoy a large share of the global battery market. During 2003–2004, the Chinese lithium-ion battery industry developed dramatically. The production of cobalt acid lithium and nickel acid lithium, as well as the invention of a new manufacturing technique to extract lithium from salty lakes, could drastically reduce the importation of anode materials for lithium-ion batteries.

3 LITHIUM-ION BATTERY TECHNOLOGY IN CHINA

The demand for lithium-ion rechargeable batteries has been driven by the rapid growth in the use of electronic portable equipment, such as cellular phones, laptops, and digital cameras. In addition, the expectation that rechargeable batteries will play a large role in alternative energy technology, as well as in electric bikes (e-bikes), EVs, hybrid vehicles, and PHEVs, has made the development of lithium-ion rechargeable batteries a fast-growing industry in China and the world. The first commercial lithium-ion rechargeable battery, introduced by Sony Japan in 1989, used graphite as the anode. Since then, Chinese companies have been developing and producing lithium-ion batteries for portable applications. Recently, Chinese companies that manufacture lithium-ion batteries grew by several hundred. Large companies (such as BYD Company Limited; Shenzhen BAK Battery Co., Ltd.; Shenzhen B&K Technology Co., Ltd.; Tianjin Lishen Battery Joint-Stock Co., Ltd.; and others) hold a large share of the global market. The performance characteristics of lithium-ion cells from various manufacturers are given in Table 6.

TABLE 6 Characteristics of Lithium-Ion Cell/Module from Various Manufacturers

Manufacturer	Cell/ Module	Voltage (V)	Capacity (A•h)	Weight (kg)	Specific Energy (Wh/kg)	Power Density (W/kg)	Cycle Life	Application
CITIC Guoan MGL	M	24	13	2.3	92	151	500	Bike
	M	3.8	10	0.10	8	–	500	Phone
	M	3.8	5	0.5	76	125	500+	Miner lamp
	M	48	100	3.2	120	134	450	EV
Beijing Green Power	C	3.8	10	0.110	118	84	540	Bike
Tianjin Lishen Battery Joint-Stock Co., Ltd.	C	3.6	5.4	0.205	128	92	600	Notebook
	C	3.6	13	0.360	117	91	500	Bike
	C	3.6	8	0.245	121	94	500	Bike
Tianjin Lantian	C	3.6	2	0.044	–	–	–	Comm
	C	3.6	18	0.80	115	100	800	EV/bike
	C	3.6	100	2.6	106	138	460	EV/bike
	C	3.6	3	0.125	87	147	450	Power tools and HEV
	M	24	20	10.0	52	53	400	EV/motor bike
Xingheng	M	–	15	0.88	63	1,250	450	HEV/EV
	M	–	7.5	0.44	68	1,800	450	HEV
	M	–	10	0.37	100	200	500	EV

TABLE 6 (Cont.)

Manufacturer	Cell/ Module	Voltage (V)	Capacity (A•h)	Weight (kg)	Specific Energy (Wh/kg)	Power Density (W/Kg)	Cycle Life	Application
Suzhou Phylion Battery Co., Ltd.	C	3.7	10	0.36	102	86	500	E-bike
Shenzhen BAK Battery Co., Ltd.	C	3.7	1.8	0.054	123	100	–	Portable
	C	3.7	0.95	0.028	125	99	400+	Portable
ABT, Inc.	C	3.7	5	0.270	69	76	>700	Portable
GBP Battery Co.	C	3.7	60	1.80	123	82	>550	EV
Hyper Power Co.	C	3.7	1.15	0.037	115	78	>600	Portable
Shenzhen B&K Technology Co., Ltd.	C	3.8	0.100	0.007	100	–	400	Portable
Tianjin Blue Sky	C	3.7	60	1.8	122	80	>500	EV/bike
BYD Company, Ltd.	C	3.7	1.8	0.046	144	98	>400	E-bike
EMB Battery Co.	C	3.7	2.1	0.045	172	88	300	E-Bike

The capacity of lithium-ion cathode materials needs to be improved. Obstacles to improving electrolyte include cost and functional additives, as well as foreign patent protection.

Lithium-ion batteries, whether for EVs, e-bikes, or consumer electronics, are all produced by using similar processes, described in depth in Gaines and Cuenca (2000). Hence, a single manufacturer can produce battery sizes for a wide range of applications, from portable consumer electronics to EVs. Lithium-ion batteries can be designed for high power or high energy, depending on cell size, thickness of the electrode, and relative quantities of the material used. High-power cells are generally smaller in order to dissipate the higher heat load. Both types use the same current collectors and separators. Lithium resources are abundant in China. As of 2000, China was the second largest producer of lithium in the world and, in 2004, it produced 18,000 metric tons.

Most Chinese companies producing lithium-ion batteries do so for portable applications. Large companies have undertaken research and development with the help of joint ventures and/or partnerships with companies from Japan, Europe, and the United States. Section 3.4 provides summaries of joint ventures and partnerships. These companies, which include BYD Company Limited; EMB; GBP; Suzhou Phylion Battery Co., Ltd.; Xingheng; Tianjin Lantian; Tianjin Lishen Battery Joint-Stock Co., Ltd.; Beijing Green Power; and CITIC Guoan

MGL, are developing lithium-ion batteries for e-bike, EV, and HEV applications — with particular focus on EVs and e-bikes.

E-bikes have been by far the most successful battery electric vehicle application in history, with an estimated cumulative production of ~30 million by 2007. At the heart of e-bike technology is the rechargeable battery. The core rechargeable battery technology used in e-bikes is VRLA, or “sealed lead-acid,” and lithium-ion batteries.

Lithium-ion battery packs for e-bikes range from 24 to 37 V and have capacities of 5–60 A•h. The market for lithium-ion e-bikes in China is still small. In Japan and Europe, however, lithium-ion and NiMH are the dominant battery types, although annual e-bike sales (200,000/yr and 100,000/yr, respectively) are significantly lower than those in China.

In terms of traction battery technology, great achievements have been made in NiMH and lithium-ion/lithium-polymer battery technology. Research teams are:

- Beijing Powertronics Battery Co., Ltd. (lead-acid batteries)
- Tianjin Peace Bay Co., Ltd.
- Inner Mongolia Rare Earth Ovonic High-Power Ni/MH Battery Co., Ltd.
- Shenzhou Science
- Chunlan (NiMH battery technology)
- Zhong Hengrun
- Tianjin Lantian Double-cycle Tech Co., Ltd.
- Phylion Battery Co., Ltd.
- Beijing Green Power Technology Co., Ltd.
- MGL
- Thunder-sky (lithium battery technology)

3.1 PROCESS TO IDENTIFY COMPANIES IN CHINA DEVELOPING LITHIUM-ION BATTERY TECHNOLOGY

Initially, 32 web sites were identified as related to battery companies in China. These sites did not include company-specific sites. These sites were studied in detail to identify individual sites for battery companies, including those that mentioned such battery technologies as lead-acid, nickel-metal hydride, lithium-polymer, and lithium-ion. Approximately 260 company-specific sites were identified, and they included companies related to export, sales, research and development, and manufacturing battery technologies.

These 260 sites were studied in detail, and a hierarchy of battery technology criteria was established, as shown in Figure 1. For screening these companies initially, a set of “Selection Criteria” was set up to narrow down the list to companies involved in developing lithium-ion battery technology:

1. Sales
2. Research

3. Development
4. Manufacturing
5. Exporting
6. Size
7. Technology availability

On the basis of these criteria, 43 companies (see Appendix D, List A) were identified that are in business to pursue lithium-ion battery technology for various applications. These applications predominantly include camcorders, telephones, and a variety of electronic gadgets. Interest in technology development for transportation applications is strong and quite evident, particularly at large companies, universities, and institutions.

The number of appropriate companies was subsequently narrowed down to 27 (by using the criteria II shown in Figure 1) by eliminating sales companies (see Appendix D, List B). Five large institutions are also involved in the development of lithium-ion battery technologies.

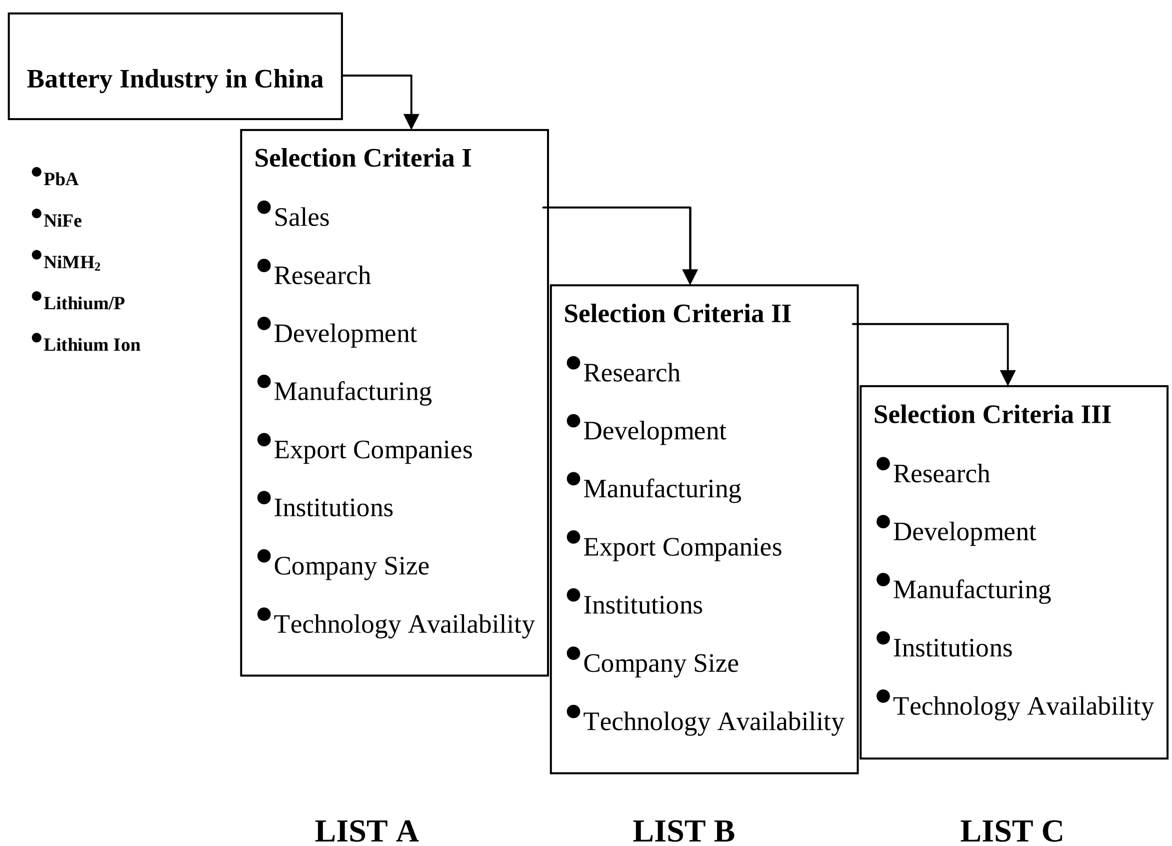

FIGURE 1 Process Used to Identify Companies in China Involved with Lithium-Ion Batteries

In the next step, the exporting companies were eliminated. These companies do not develop any products; they simply buy products from other companies and export them. Also, extensive discussions were held with representatives from the China Automotive Technology and Research Center (CATARC) to narrow down of the final list of companies, institutions, and universities for the detailed analysis and evaluations. These organizations focus their work on lithium-ion technology and are shown in Appendix D, List C.

Section 3.2 provides details on lithium-ion battery technologies at several companies and institutions that were visited.

3.2 TECHNOLOGY AT VARIOUS INSTITUTIONS IN CHINA

3.2.1 Tsinghua University (Department of Automotive Engineering Beijing, 100084)

The university's Automotive Department started its research activities for EVs in 1995, for hybrids in 1998, and for fuel cell hybrid vehicles in 1999. The university is working with the following battery companies on lithium-ion batteries for vehicular applications:

- Shenzhen B&K Technology Co., Ltd.
- Thunder Sky
- MGL New Energy Technology Co., Ltd.
- Oriental Polymer
- Huanyu Battery Co.

The department has an excellent facility to test and evaluate complete vehicular systems, as well as batteries at the module and pack level. Battery testing and evaluations are conducted by using the following:

- National Standards of the PRC
- USABC Battery Test Manual
- Partnership for a New Generation of Vehicles Battery Test Manual
- FreedomCAR Battery Test Manual
- Testing Standards of Japan
- Other testing standards, such as those developed by American Society of Mechanical Engineers (ASME)

Currently, it is evaluating hybrid and fuel cell hybrid buses with lithium-ion batteries. Batteries are 100 A•h, and a pack contains 30 cells. This evaluation is conducted for China's 863 Program. Oriental Polymer Company in Beijing is supplying an 18-kW fuel cell. Thunder Sky battery Company has provided a 30 A•h lithium-ion cell with 100 cells per pack in series.

A hybrid bus has been evaluated for 1,250 km without any degradation in battery performance. Similarly, a fuel cell hybrid bus has been evaluated for 2,340 km without any degradation in performance.

Other research includes:

- EV Structure Design
- Parameter Match and Optimization of EV Powertrain System
- Optimization of Energy Management Strategy
- EV Controller Design
- EV Communication Network
- EV Failure Diagnostics
- Other EV Subsystem Testing
- EV Assembly and Road Test

The department's focus is research on EVs, HEVs, PHEVs, and fuel cell electric vehicles (FCEVs), with an emphasis on battery applications. Involved in this research are 2 professors, 4 associate professors, 2 engineers, 5 part-time experts, 4 post-doctoral students, 4 doctoral candidates, and 13 master's degree students. The university has six patents and four applications pending in China on battery thermal management, EV controller design, and electronics for vehicles. The department is working with General Motors on fuel cell vehicles; however, the details of the involvement are unclear.

3.2.2 China Electrotechnical Society (46 Sanlihe Road Beijing 100823)

The China Electrotechnical Society has 123,000 members. The society is a clearinghouse for electrotechnical research. It conducts studies on battery technology markets for EVs and HEVs. Recently, the society completed a preliminary technology study on fuel cells and fuel cell hybrid vehicles. The study was conducted for its membership and the Chinese government. The society would not provide a copy of the report.

The Chinese government encourages the development of lithium-ion battery technology for vehicular applications. The Chinese government is providing incentives and grants for Chinese-owned and -operated companies — as much as 75% of the total cost, which covers most operating and capital expenses. For small companies, these incentives can be upwards of 85%.

China wants to export not only lithium-ion batteries for electronics applications, but it also wants to export batteries and advanced vehicles. Currently, China has 18 million battery-operated bicycles, of which 40,000 operate on lithium-ion batteries, and the rest on lead-acid batteries.

3.2.3 CITIC Guoan MGL MGL New Energy Technology Co., Ltd. (Beijing 102200)

MGL is located in Beijing Zhongguancun Science Park. It is engaged in the R&D and production of new composite metal oxide materials and high-energy-density lithium-ion secondary batteries. MGL is primarily supported financially by the CITIC Guoan Group, a wholly owned subsidiary of China CITIC Group. The CITIC Guoan Group is involved in such industries as information, new materials, comprehensive mineral resources exploration, tourism, and real estate. CITIC was founded in October 1979 by Rong Yiren, former Vice Chairman of the Peoples Republic of China. Through more than 20 years of development, CITIC has built a large-scale international enterprise group with total assets of 700 billion Ren Min Bi (RMB) ($933.34 million).

MGL ranks as China's largest manufacturer of the lithium-ion battery cathode material, $LiCoO_2$, and it will be the first to market the new cathode materials, $LiMn_2O_4$ and $LiCoO_{0.2}Ni_{0.8}O_2$. MGL states that it emphasizes quality control, and has passed the certification of both New and Hi-Tech Enterprise Standards and IS09001:2000. With its particular synthesis method, MGL appears to efficiently produce cathode materials of superior performance and reliability in an environmentally friendly way. Since incorporation, MGL holds the monopoly in China's lithium-ion battery cathode materials market and now appears to be at the forefront of the industry. Besides cathode materials, MGL also produces lithium-ion secondary batteries of high energy density and high capacity for power and energy storage — the capacity ranges from several ampere-hours to several hundred ampere-hours. As China's first power-battery manufacturer, MGL appears to lead the industry in the marketing of high-capacity lithium-ion secondary batteries, used in the Beijing Municipality's trial electric bus fleet.

The MGL R&D center is located in Beijing. MGL has 850 employees, including 103 Ph.D. engineers and scientists. The R&D center encompasses 5,000 m^2 and includes advanced battery analytical, manufacturing, testing, and assessing equipment.

Major products of MGL's materials division include $LiCoO_2$ (2,300 tons/year), $LiMn_2O_4$ (1,450 tons/yr), and $LiCo_{0.2}Ni_{0.8}O_2$ (340 tons/yr). These oxide materials are indispensable to high-voltage (4-V) and high-energy-density lithium-ion secondary batteries. Over the past 10 years, lithium-ion secondary batteries have taken the place of NiMH and NiCd secondary batteries, which are used widely in mobile phones, laptops, and other electronic applications.

Instead of the commonly used solid-state synthesis method, MGL has adopted a unique method to synthesize materials, which is an efficient and simple process featuring zero emissions and low energy consumption. Feedback from lithium-ion battery manufacturers in China and abroad indicates that MGL's battery cathode materials have excellent and steady electrochemical performance. However, despite the rapid development of lithium-ion batteries over the last 10 years, limited cobalt resources and the poor thermal stability of $LiCoO_2$ limit the application of lithium-ion batteries.

For the past 10 years, with the support of the State and local governments, MGL has been focusing on the research and development of new lithium-ion battery cathode materials, notably spinel $LiMn_2O_4$ and layered $LiCo_{0.2}Ni_{0.8}O_2$. Experiments indicate that the superior thermal stability and steady charge-discharge performance of $LiMn_2O_4$ and $LiCo_{0.2}Ni_{0.8}O_2$ are quite compatible with various types of lithium-ion batteries. Recently, MGL's $LiMn_2O_4$-based and $LiCo_{0.2}Ni_{0.8}O_2$-based lithium-ion batteries have been used in energy-saving and environmentally friendly industries. China is poor in cobalt resources, but rich in manganese and nickel resources. MGL is developing China's lithium-ion battery materials industry by applying its specific synthesis method.

In comparison with NiMH and NiCd secondary batteries, lithium-ion secondary batteries have higher cell voltage, are smaller and lightweight, offer more flexibility under different temperatures, and do not have memory effects. Reportedly, these batteries do not emit pollution. At present, lithium-ion secondary batteries have an energy density of two to three times that of lead-acid batteries and around twice that of NiMH and NiCd batteries. Small lithium-ion batteries have been widely used in small high-end electronic devices (such as mobile phones and laptops). The physical-chemical properties of cathode materials, separators, and electrolytes play an important role in the reliability of lithium-ion batteries, and carbon — as the current anode material — has realized only one-tenth of its theoretical capacity. The new organic, inorganic, and metallic materials that MGL is developing will improve the physical-chemical performance of lithium-ion batteries and expand their applications, and solid and inorganic electrolytes will drastically improve the reliability and safety of lithium-ion batteries.

Recently, MGL's independently developed high-capacity lithium-ion batteries have been used successfully in Beijing's trial fleet of electric buses. Research indicates that the new lithium-ion batteries could accelerate the industrialization of EVs, and show potential in such applications as mobile communications, nighttime power storage, wind- and solar-power storage, backup emergency power, backup power for vehicles, and portable power.

3.2.3.1 Attributes of MGL's Lithium-Ion Battery

- Safe, excellent cycle performance and economics: the cathode material of MGL's power battery is spinel $LiMn_2O_4$, produced by MGL's unique synthesis method, which is yielding a far more economical and thermally stable product than $LiCoO_2$.

- Flexible configuration with aluminum packaging and stainless-steel casing.

- Stable output under large charge/discharge currents and different temperatures (-25~50°C).

- High voltage (3.8 V) and high energy density (>120 Wh/kg).

- No memory effects and non-polluting.

3.2.3.2 100-A•h $LiMn_2O_4$-Based Battery for EVs

- Constant current charge capacity (96%)
- Lower impedance (<0.85 mΩ)
- Flexible configuration
- Prominent safety performance
- High specific energy (>120 Wh/kg)
- Easily connected in series or parallel

3.2.3.3 Lithium-Ion Battery for Miner's Lamp

- High safety performance
- Lightweight, high specific energy
- Flexible capacity (4, 5, and 6 A•h)
- Long cycle life

In addition, MGL's LP 188270 series battery has passed the safety test by North Automotive Quality Supervision Test and Assessment Research Institute 863 (this is a National Advanced Technologies Development Program in China) Power Battery Testing Base under the standard GBIZ 18333.1-200 and GB/T 18827-2000. The testing results show that MGL batteries have superior safety performance, making the lithium-ion battery the ideal power source for a miner's lamp. Some manufacturers of miner's lamps in China have used MGL's batteries.

3.2.3.4 Battery-Management System for HEVs

- Measurement of current, voltage (cell and total), and temperature
- Calculation and display of SOC and state of health
- Cell balancing
- First protection (battery-management system): over-voltage (cell, pack), current, temperature
- Communication: CAN (ECU), RS-422 (internal), RS-232 (monitoring PC)
- Pre-charge control
- Second protection: over-voltage (cell), short current protection by heat sink (ratio of the porous sink height to the jet nozzle width).

3.2.3.5 MGL Battery-Powered Electric Vehicles

- MGL participated in the Challenge Bibendum 2004 held in Shanghai, China, and the Challenge Bibendum 2006 in Paris, France. At both events, MGL featured its independently converted pure EV powered by an MGL lithium-ion power battery. MGL received awards on both occasions for parameters such as acceleration, noise, fuel efficiency, radiation, and emissions.

- MGL's vehicles have passed the comprehensive EV performance tests performed by the Road Transportation Testing Center of the Road Science Research Institute of China's Ministry of Transportation.

- Beijing's Olympics electric bus, powered by an MGL 100-A•h power battery, has covered an cumulative range of 20,000 km during the past two years, and the tests have demonstrated high electrochemical and safety performance of its battery.

3.2.3.6 Lithium-Ion Power Battery Packs for Electric Two-Wheelers

- 24 V with 13-A•h aluminum packaged, weight 2.3 kg
- 24 V with 8-A•h stainless-steel packaged, weight 2.45 kg

3.2.3.7 Other Information on MGL

- MGL holds several patents (perhaps between 15 and 25) on cathode materials, anode materials, a battery management system, electronics, and other areas of battery technology in the United States, Japan, China, and Korea.

- The cost of the lithium-ion technology at the cell level is 5–9 RMB/Wh ($0.67–1.20/Wh).

- MGL is working with a U.S. company on a battery for electric and hybrid vehicle applications. However, MGL did not provide the name.

- MGL is receiving grants from local, district, and national government — the total amount is around 10 million RMB ($1.34 million) per year.

- MGL is willing to provide cells, modules, and packs for benchmarking in the United States.

3.2.4 Beijing Green Power Technology Co., Ltd. (Beijing 100086)

Beijing Green Power Technology Co., Ltd., has set up research laboratories, as well as applied laboratories for technology scale-up. In the research laboratory, the company conducts research on the materials for cathodes, anodes, and separators. In applied materials, the laboratory conducts research on cells and module development and performs testing and evaluation.

After three years, Green Power has formed its own technical research direction on the aspects of lithium-ion power cell technology and cathode material with technological success.

Green Power has invested 20 million RMB ($2.67 million) to set up a product line of power cell capacity of about 20,000 A•h per day. Green Power has invested 10 million RMB ($1.34 million) to set up a product line of spherical lithium cobalt oxide cells with a capacity of 300 tons per year. Additionally, 15 million RMB ($2.00 million) was invested in setting up a product line of three-element cathode material with 300 tons per year, which was put into production in July 2006. The production capacity is 10,000 A•h per day.

3.2.4.1 Lithium-Ion Battery Technology

Electric Bike: Green Power uses its specific technology to fabricate cell structures, along with a new cathode material ($LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$) and a new electrolyte (LiBOB), for its high-power cells and modules. The company has developed a 10-A•h cell for e-bike application. The cost of this cell is estimated at 135 RMB ($18.00) (this is only the cell cost). The e-bike battery pack has 10 cells (10 A•h each), and so far the company has sold 540 e-bikes with this battery and accumulated 30,000 km of on-the-road performance without battery degradation.

Electric Bus: A 100-A•h cell has been designed for the electric bus application. In the electric bus, the battery pack has 500 cells with 100-A•h capacity for each cell. This bus is being evaluated on the road and has accumulated 20,000 km; battery capacity is at 98% of the original capacity. A battery pack has 400 V and provides 50 A•h of capacity. Total energy is greater than 200 kWh. The pack is designed to operate at -20°C to +55°C. Green Power is working on a cooperative program with Beijing Science and Engineering University, which is evaluating electric buses for the 2008 Olympics. Green Power has built five buses so far. A thermal management system used in this bus maintains a temperature with a differential between 1 and 3°C. The cost of a 100-A•h cell is estimated at 1,700 RMB ($226.67). There are additional costs for making a battery pack. Green Power will not elaborate on how much cost is added to the cell cost.

Hybrid Electric Bus: For the HEV bus application, Green Power is using 100 cells, each with a capacity of 100 A•h. Each cell weighs 3.0 kg. Pack voltage is 360 V, and the power is 54 kW (with energy around 34 kWh). A hybrid bus that is similar to a U.S. 40-ft version has accumulated 10,000 km with very little degradation in performance. Green Power is cooperating with Tsinghua University on this program. According to Tsinghua University, Green Power's battery design and performance are comparable with those of other lithium-ion batteries evaluated by the university. Green Power has built six HEV buses so far.

3.2.4.2 Other Information on Green Power

- Green Power has 10 patents in China on cathode and anode materials, battery management systems, electronics, and other areas of battery technology. It is currently marketing in China; however, Green Power wants to expand its market abroad in the near future.

- Green Power is obtaining 10 million RMB ($1.34 million) per year in grants from the Chinese 863 Program, which is an advanced technology program.*

- Green Power has a strong desire to work with a company in the United States.

- Green Power is very interested in providing cells, modules, and packs for benchmarking in the United States.

3.2.5 Tianjin Institute of Power Sources (Tianjin 300381)

Dr. Wang Ji Qiang, Chief Engineer and Professor at the Tianjin Institute of Power Sources, is well known in China and is involved in the 863 Program as it relates to advanced battery development for the Beijing Green Olympic Games. He serves on several technologically influential committees with the Chinese Government, works closely with lithium-ion battery development companies, and knows the technology across the country. He also looks after the activities of the "Testing Center of Chemical and Physical Power Sources of Ministry of Information Industry."

Tianjin Institute of Power Sources is one of the two national laboratories involved in battery testing and evaluation activities and programs. This testing center of chemical and physical power sources of the Ministry of Information Industry of China was established in 1985. It is claimed to be the largest, most comprehensive, most authoritative independent quality-testing center for chemical and physical power sources.

The testing center of the Chemical and Physical Power Sources of China Ministry of Information Industry (QSTC) is attached to the Tianjin Institute of Power Sources. QSTC is located in Nankai District, Tianjin City, occupying 5,500 square meters. The testing center has 500 items of advanced testing equipment and instruments and more than 30 million RMB ($4.00 million) in fixed assets. At present, 76 staff members are in the center laboratory, and 48 of those are professors and engineers. The QSTC center laboratory undertakes programs of the 863 Program, carrying out the tasks of EV battery supervision and test technology. Many types of nickel metal hydride batteries, lithium-ion batteries, and super capacitors used in EVs have been tested and evaluated at QSTC.

The QSTC center laboratory has been authorized by the National Authorization Committee (#L0591) and China National Certification and Authorization Supervision and Management Committee as a qualified laboratory for calibration and measurement. This center is

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* In March 1986, Deng Xiaoping launched China's National High-Tech Research and Development Program (also known as the "863 Program" — see www.863.org.com). The overall goals of the 863 Program are to:

- Bridge China's gap against developed countries in high-tech frontiers by pooling resources in selected high-tech fields.
- Drive science and technology advances in other relevant fields.
- Produce high-caliber technological R&D talents.
- Create opportunities for formation of high-tech industries and lay foundations for realizing national higher-level economic and social development by around 2000.

one of four laboratories in the world qualified to calibrate photovoltaic scales. It is also the government-appointed laboratory to test imported and exported battery-related products (as well as those used for passenger trains). The center laboratory is the consigned organization for the testing of storage batteries for Underwriters Laboratories (UL) certification and is the appointed laboratory of the China Quality Authentication Center. QSTC has acquired the hardware and software of China compulsory 3C product certification (voluntary) and is able to offer relative technical service and support.

The Center’s quality guarantee system is based on the requirements of ISO/IEC guideline 17025:2005, “Universal Competence Requirements for Testing and Calibration Laboratory.” QSTC has also been approved as a National Defense Science and Technology Laboratory by the National Defense Science and Technology Industrial Laboratory Committee.

The Center appears to have excellent testing equipment and to follow international testing standards. It is able to test basic electro-chemical performance, environmental evaluation, and safety for chemical and physical power sources by using standards established by the IEC, UL, United Nations, Japan Institute of Standards, and the military. The power sources can be Zn-Mn, lithium-ion, silver-zinc, Zn-air, and lead-acid batteries series. NiCd, alkaline, nickel metal hydride, special kinds of batteries, silicon solar cells, thermoelectric generation series, thermoelectric cooling modules, and sensors can also be evaluated at this Center.

Since its foundation, QSTC has completed many tests and experiments (such as national testing, supervision of selective examination, performance evaluation, product grading evaluation, quality testing, comparison experiments, product judicial judging, technical judging, arbitration testing, export and import testing, and feasibility evaluation). At the same time, the center laboratory is conducting research on various power sources charge/discharge equipment, testing technology, and performance evaluation methods. The Center is actively providing technology support and consultation to its clients to accelerate the quality of chemical and physical power sources in China. QSFC has had extensive connections with counterparts at home and abroad. The Center keeps the testing results from clients confidential.

The Center has the following testing and evaluation equipment:

- Pulsed solar simulator (German made)
- Automatic absorption spectrometer; made by Perkin-Elmer (United States)
- Digatron (charge/discharge instrument) (German made)
- Environmental testing equipment
- High-power charge/discharge instrument (German made)
- Arbin charge/discharge instrument (U.S. made)

Since 2001, a number of national projects have focused on the development of lithium-ion batteries and related materials. There are two major basic research programs:

1. High-energy-density lithium batteries
2. R&D on new materials for lithium-ion battery applications

The most important part of these two programs is a major technical innovation program on the development of advanced batteries for EVs and HEVs, as well as for fuel cell electric vehicle applications. There are also many programs supported by different state agencies and local governments. These programs are related to basic and applied research on new battery systems and new materials, as well as to pilot or mass production and trial applications of newly developed materials and advanced batteries.

3.2.5.1 Progress in R&D of Advanced Materials for Lithium-Ion Batteries

In 2001, a National Major Program on R&D of advanced rechargeable battery systems with a specific energy of 200–250 Wh/kg was set up and has since been conducted by a joint research group that includes Wuhan University, Tianjin Institute of Power Sources, Beijing Physical Institute of China Academy, and Harbin Engineering University. To achieve the above goal of specific energy, the requirements for a 3.5–4.5-V system were set up as follows: (1) advanced negative material specific capacity greater than 450 mA•h/g and more than 85% efficiency for first charge-discharge cycle and (2) advanced positive material specific capacity greater than 200 mA•h/g.

Possible candidate materials were selected, and some of them were thoroughly investigated. Evaluations encompassed new material synthesis, property evaluation, modifications, and performance of materials in the prototype cells. Among those explored further were Li-Ni-Co-O and Li-Ni-Co-Mn-O systems for positive materials and carbon. C-Si composite and lithium-alloy systems were evaluated as negative materials. Li/S or polymer-S systems with lower voltage (below 3 V) were also investigated. Typically, some nano-size and surface-treatment concepts were used for developing advanced battery materials. An optimum combination of Li (Ni, Co, Mn) -positive material with a specific capacity of 220 mA•h/g and C-Si composite negative material with a specific capacity of 550 mA•h/g and 91% efficiency for first cycle was demonstrated in both 18650 and soft packaged cells. These cells exhibited specific energy between 236 and 267 Wh/kg.

3.2.5.2 Progress in Developing Lithium-Ion Batteries for EVs, HEVs, and FCEVs

In 2001, Major National Programs on R&D of advanced rechargeable battery systems for EVs, HEVs, and FCEVs were initiated. These programs are part of the Chinese 863 Program (Electrical Project). R&D of high-energy-type (capacity range of 50–200 A•h) lithium-ion batteries for EV and high-power (capacity of 8–40 A•h) lithium-ion batteries for HEVs and FCEVs were developed. Liantian Company, Xinyuan Company, Leitian Company, and Beijing Institute of Non-ferrous Metals are involved in the development of these batteries. The National Testing Center reported a good deal of progress in evaluations related to specific energy, cycle life at deep depth of discharge, and simulation of vehicle running conditions. High-power, 15-A•h batteries are used in fuel cell/battery hybrid cars for demonstration. These batteries have been crash tested according to a national standard, and no hazard was observed.

3.2.5.3 Progress in Developing New Lithium-Ion Batteries for E-Bike Applications

D-size cells with 5-A•h capacity and 10–15-A•h prismatic cells with Al-doped $LiMn_2O_4$ and $Li(Ni_xCo_yMn_z)O_2$ positive are being produced for e-bike applications. Also, high-power 18650 and 26650 cells with $Li(Ni_xCo_yMn_z)O_2$ and $LiFePO_2$ positive materials have been successfully developed and can run on a 10-h rate (C) of discharge.

3.2.6. Tianjin Lishen Battery Joint-Stock Co., Ltd. (Tianjin 300384)

Tianjin Lishen Battery Joint-Stock Co., Ltd., established in 1998, is located in the Tianjin Huayuan Hi-Tech Industry Park. The company occupies an area of 85,000 m^2 and employs 5,000 people. It has a capitalization of 600 million RMB ($80.00 million), and its total investment has reached 1.5 billion RMB ($200.00 million). Tianjin Lishen Battery Joint-Stock Co., Ltd., has imported advanced automatic production equipment from Japan, so the production of lithium cells is completely automatic.

By 2004, the company had an annual production capacity of 200 million cells, which consist of more than 100 specifications, ranging from cylindrical to prismatic lithium-ion batteries. Relying on its intellectual property rights, with the innovation-oriented institution and supportive policies, Tianjin Lishen Battery Joint-Stock Co., Ltd., has become one of the largest manufacturers of lithium-ion batteries and possesses the most advanced technology in China. The Chinese Version of *Forbes* magazine ranked Lishen as number eight in its "List of Highest Potential Enterprises" in China for 2006.

Since its inception, Tianjin Lishen Battery Joint-Stock Co., Ltd., has been focusing on management — putting quality as the top priority and pursuing battery innovations. The quality and performance of the company's cells appears to be world-class. Tianjin Lishen Battery Joint-Stock Co., Ltd., has obtained the certification of ISO9001-2000, CE (Conformité Européenne; French for "European Conformity"), UL, and ISO14001. These certifications have paved the way for the company to capture international and domestic market shares. Tianjin Lishen Battery Joint-Stock Co., Ltd., is supplying batteries to corporations such as Motorola ESG and Samsung. Recently, the company set up branches in North America, Europe, Korea, Taiwan, and Hong Kong in an effort to establish a powerful worldwide-marketing network. Its business is 60% export and 40% domestic.

Tianjin Lishen Battery Joint-Stock Co., Ltd., is said to have always valued technology research highly, and it has increased its investment in R&D. Recently, it has set up a Postdoctoral Workstation and a National Technology Center. In 2005, it has established a world-class Safety Test Center. These efforts ensure continuous development of quality battery products.

Tianjin Lishen Battery Joint-Stock Co., Ltd., recently developed a new type of lithium-ion battery, and its cathode material is $LiFePO_4$ from Valence. Battery performance is good and safe. This battery is being evaluated by CATARC in battery electric vehicles. It also makes 18650 cells at this plant.

Tianjin Lishen Battery Joint-Stock Co., Ltd., makes both prismatic and cylindrical cells. The prismatic cells are used in mobile phones, portable PCs, digital cameras, MP3 players, and other high-technology devices. The cylindrical cells are used in portable PC, E-book, and satellite communication devices; digital video cameras and portable DVD players; and portable printers/portable scanners. High-power prismatic cells are designed for e-bikes, EVs, HEVs, and power tools.

Last year, the company sold 33,000 lithium-ion batteries for e-bikes and provided batteries for seven electric buses, four hybrid buses, and two fuel-cell-battery hybrid buses. These vehicles are now being evaluated at various universities and test centers.

Tianjin Lishen Battery Joint-Stock Co., Ltd., has 22 patents on all aspects of lithium-ion battery technology, as well as on manufacturing techniques. These patents are held in China, the United States, Japan, Europe, Korea, and Taiwan.

The Chinese government has awarded Tianjin Lishen Battery Joint-Stock Co., Ltd., with an initial 50 million RMB/year ($6.67 million/year) for three years and 80 million RMB/year ($10.76 million) for two years of subsequent work in manufacturing. Funding was possible because the company is located in Tianjin Huayuan Hi-Tech Industry Park, which is a declared tax-free zone.

The estimated cost of its cylindrical cell is 7 RMB/Wh ($0.93/Wh), and the estimated cost of the prismatic cell is 6 RMB/Wh ($0.80/Wh). The estimated cost of a high-power cell is 12 RMB/Wh ($1.60/Wh).

3.2.7 Tianjin Lantian Double-Cycle Tech. Co., Ltd. (Tianjin 300384)

In 2000, China Electronic Technology Group Corporations and Tianjin Metallurgical Group Co., Ltd., founded Tianjin Lantian Double-Cycle Tech. Co., Ltd., a high-tech enterprise. With capital of 93 million RMB ($1.24 million), it is specializes in research, development, and marketing of lithium-ion batteries and EVs. It is also engaged in research, development, and production of NiMH battery technology. The company has more than 500 employees, with an R&D staff of more than 150, including 30 postdoctoral fellows and 38 Ph.Ds.

The company has undertaken the EV project of the National 863 Program. A number of Tianjin's key projects include the development of lithium-ion batteries, an efficient electric machine, a controller, e-bikes, and EVs and associated parts. The company holds six patents, and six patents are pending. Tianjin Lantian Double-Cycle Tech. Co., Ltd., is certified by ISO 9001-2000, CE, and UL.

Tianjin Lantian Double-Cycle Tech. Co., Ltd., receives a 50 million RMB ($6.67 million) grant per year from the government. Its production facility is, at best, semi-automatic. Last year alone, the company sold 27,000 e-bikes with lithium-ion batteries at a cost of 3,000 RMB/bike ($400/bike). The company is working on an EV bus battery, and it has provided six 500-A•h batteries for testing and evaluation. These batteries are being developed within the National 863 Program.

3.2.7.1 Cell Production and Applications

Tianjin Lantian Double-Cycle Tech. Co., Ltd., produces three different cells as the high-energy and high-power lithium battery for EVs and cells for e-bike applications. Table 7 provides details on these cells.

TABLE 7 Tianjin Lantian Double-Cycle Tech. Co., Ltd., Cells for E-Bike Applications

Cell Model #	Capacity (A•h)	Voltage (V)	Weight (kg)	Dimensions (mm × mm)	Operating Temperature (°C)	Cycle Life (80% DOD)
ICR 47/205	18	3.6	0.8	47 dia × 205	-20 ~ 55	800
ICR 50/380	55	3.6	1.8	50 dia × 380	-20 ~ 55	800
ICR 65/400	100	3.6	2.6	65 dia × 400	-20 ~ 55	800

Table 8 lists details on high-power lithium-ion batteries for power tools and HEVs.

TABLE 8 Tianjin Lantian Double-Cycle Tech. Co., Ltd., Cells for Power Tools and HEVs

Cell Model #	Capacity (A•h)	Voltage (V)	Rate Discharge (C)	Weight (kg)	Dimensions (mm × mm)	Operating Temperature (°C)	Cycle Life (80% DOD)
ICR 45/150	8	3.6	15	0.45	45 dia × 150	-20 ~ 55	800
ICR 25/50	1.8	3.6	15	0.055	25 dia × 50	-20 ~ 60	800
ICR 32/65	3	3.6	10	0.125	32 dia × 65	-20 ~ 60	900

Table 9 shows details on other lithium-ion cells for additional applications for e-bikes.

TABLE 9 Details on Other Lithium-Ion Cells for E-Bikes

Cell Model #	Capacity (A•h)	Voltage (V)	Time Discharge	Weight (kg)	Volume (L)	Cycle Life
36V/9A•h	9	36	1 h 48 min (5A)	2.8	3.5	600
24V9A•h	9	25	1 h 48 min (5A)	2	2	600

Table 10 provides details on lithium-ion cells for electric motorcycles and other EVs.

TABLE 10 Tianjin Lantian Double-Cycle Tech. Co., Ltd., Cells for Electric Motorcycles and Other Electric Vehicles

Cell Model #	Voltage (V)	Max Discharge Current (A)	Weight (kg)	Volume (L)	Cycle Life
24 V/20 A•h	24	20	10	5.5	>800
24 V/55 A•h	24	60	17	10.5	900
36 V/20 A•h	36	20	12	7.0	900
36 V/55 A•h	36	60	23	13.5	800
288 V/100 A•h	288	150	230	115	800

3.2.7.2 Other Information on Tianjin Lantian Double-Cycle Tech. Co., Ltd.

- The company wants to export its products and would like to have a relationship with U.S. companies.

- The company has designed a battery for a hybrid vehicle with a capacity of 7.5 A•h, 96 cells (12 cells per module). It has fabricated 20–30 packs for laboratory and in-vehicle evaluations.

- The company would like to provide batteries for benchmarking in the United States, and it believes that doing so will enhance its potential for cooperation.

3.2.8 Suzhou Phylion Battery Co., Ltd. (Jiangsu 215011)

Phylion is a battery technology corporation set up by Legend Capital Co., Ltd.; the Institute of Physics of the Chinese Academy of Sciences; and the Chengdu Diao Group. Phylion has 82 million RMB ($10.93 million) and a staff of more than 400. Phylion specializes in manufacturing and selling lithium-ion cells with high capacity and current. Phylion's technology is primarily used in defense, electric bicycles, lighting, portable electronics, medical equipment, and battery-operated tools.

As one of China's largest manufacturers of lithium-ion battery cells, Phylion's average volume is currently 36 million units per year. Phylion's high-capacity (10 A•h) and high-power (7.5 A•h) lithium-ion cells have successfully passed U.S. testing by Underwriters Laboratories, which paved the way for exporting the technology to the industrial world. Phylion benefited from technical assistance from the Institute of Biophysics of the Chinese Academy of Sciences (for about 15 years), funding support by The National Program #863 and #973, and further assistance from the Development and Reformation Committee (for the last 12 years). This combined funding enabled Phylion to accumulate experience as a company and establish a solid technical foundation to develop lithium-ion battery technology. Phylion has a 10 million RMB ($1.34 million) grant from the federal government to conduct basic and applied R&D on lithium-ion battery technology for e-bike, EV, and HEV applications. Furthermore, internally developed patents have been applied in the development of lithium-ion technology and methods of production. The company holds 17 patents on various aspects of lithium-ion battery technology. Phylion uses $LiMn_2O_4$ as the cathode in the lithium-ion battery.

Phylion's production facility is semi-automatic. All material mixing, cell size cutting, and cell tabbing are done manually. The production equipment is imported from Japan, with 90% financial assistance from state and federal governments. In 2006, Phylion sold 52,000 packs for various applications and sold 32,000 e-bikes. The company builds 50 packs of different types for EV and HEV applications. Phylion has cooperative programs with Shanghai Automobile Group, North Automobile Group in Beijing, and Tongji University in Shanghai. At present, Shanghai Automobile Group is evaluating Phylion's lithium-ion battery in a fleet of passenger vehicles, which includes EVs, HEVs, and fuel-cell-battery hybrid vehicles. The North Automobile Group is evaluating batteries in electric buses, and Tongji University is conducting an evaluation of batteries in fuel-cell-battery hybrid vehicles.

Phylion has conducted several experiments to determine the safety of the lithium-ion battery and has provided some experimental data, which are summarized in the following sections.

3.2.8.1 Overcharging Experiment

The overcharging experiment involved charging the electric cores with the constant current and setting up the upper limit for the fixed voltage. The interior electric core will raise the dendrite growth in the cathode. The tests are summarized in Table 11.

TABLE 11 Summary of Tests Involving Charging Electric Cores with Constant Current and Setting Upper Limit for Fixed Voltage

Standard	Premise	Environmental Temperature (°C)	Charging Current	Experimental Process	Time Requirements	Result Requirements
War Industry	After charging, according to the standards	20 ± 5	0.2C 5A	Until the protective circuit functions	No	No explosion and burning
QB/T25022000 Standards of Light Industry	The cell in the state of complete discharging	20 ± 5	0.2C 5A	Make the protective circuit function	12.5 h	No explosion and burning
04 Department of Science and Technology [863 Program], Storage Battery of Electro-motion Bicycle	After charging, according to the standards; discharge for an hour	20 ± 5	1C 1(A)	The voltage reaches 5.0 V	Or charge for 90 min	No explosion and burning
National Standards GB/T 18287-2000	After charging, according to the standards	20 ± 5	3C 5 A	The upper limit of voltage is 10 V	After declining the peak value 10 min, end the experiment.	No explosion and burning
Underwriters Laboratories Standards	After charging, according to the standards	20 ± 5	Carry through the relative current and time, according to: $t_c = \frac{2.5C}{3(I_c)}$. Note: C is the standard capability. Ic is the testing current.		The testing time cannot be shorter than 48 h	No explosion and burning

3.2.8.2 Experiment with Nail Penetration

Table 12 summarizes the tests involving experiments with nail penetration.

TABLE 12 Summary of Tests Involving Nail Penetration

Standard	Premise	Environmental Temperature	Steel Needle	Experimental Process	Time Requirements	Result Requirements
War Industry	After charging, according to the standards	20 ± 5	Φ 3mm	Strongly penetrate along the radial	No requirements	No explosion and burning
Standards of Light Industry iQB/T2502-2000	After charging, according to the standards	20 ± 5	2.5 ~ 5 mm	Penetrate in the direction that the center and electrode surfaces are vertical	Place more than 6 hours	No explosion and burning
2004 Department of Science and Technology [863 Program], Storage Battery of Electro-motion Bicycle.	After charging, according to the standards	20 ± 5	φ 3 ~ 8 mm	Promptly penetrate in the direction to which the pole plate is vertical	The steel needle sticks in	No explosion and burning
Underwriters Laboratories Standards	After charging, according to the standards	20 ± 5	Bounce to the cells at the minimum acceleration of 75 g and the maximum acceleration of 125 ~ 175g within 3 ms on the face and side face of the cell			No explosion and burning, ejection ≤ 5 g

3.2.8.3 Thermal Impact

Table 13 summarizes the tests involving experiments with thermal impact.

TABLE 13 Summary of Tests Involving Thermal Impact

	Premise	Velocity of Ascending Temperature	Upper Limit Temperature	Time Requirements	Result Requirements
War Industry	After charging, according to the standards	The battery oscillates circles for four cycles between -40 ± 2°C and 70 ± 2°C. Maintain the end temperature for 2 hours in each temperature environment. The mobile time of alternating the temperature cannot be longer than 1 minute; maintain temperature for 2 hours below 25°C.			No deformation, crack, and leakage after the test; normally charge and discharge
Standards of Light Industry QB/T2502-2000	After charging, according to the standards	5 ± 1	110°C	60 min	No explosion and burning
2004 Department of Science and Technology [863 Program], Storage Battery of Electro-motion Bicycle.	After charging, according to the standards	5 ± 2	70 ± 2°C	20 min	No leakage, deformation, explosion, or burning
National Standards GB/T 18287-2000	After charging, according to the standards	5 ± 2	95 ± 2°C	30 min	No explosion and burning
Underwriters Laboratories Standards	After charging, according to the standards	5 ± 2	95 ± 2°C	10 min	No explosion and burning

3.2.8.4 Other Information on Phylion

- Phylion would like to export its products and have relationships with U.S. companies.

- Phylion would like to provide batteries for benchmarking in the United States to enhance its potential for cooperation.

3.2.9 Tongji University School of Automobile Engineering (Shanghai 201804)

In 2002, the College of Automotive Engineering was formally established in the Shanghai International Auto City in Jiading District. It was founded by merging the Automotive Engineering Department, the New Energy Center of Automotive Engineering, and the College of Automobile Marketing and Management, in accordance with the requirements of the Shanghai Automotive Industry.

The College has a staff of 64, of which 19 are full professors, 16 are associate professors, and 13 are lecturers. The College has 730 full-time undergraduate students, 124 master's degree students, and 27 doctoral students. There are 11 postdoctoral researchers in the postdoctoral mobile research center. In addition, the College has set up an internship program at the master's-degree level with several automobile companies. The College has extensive collaborative programs with several universities in Germany and the United States.

The Advanced Technologies Laboratories have the following facilities:

- Vibration laboratory
- Acoustic laboratory
- Engine dynamometer laboratory
- Fuel cell testing and evaluation laboratory
- Advanced battery testing and diagnostics laboratory
- Vehicle testing track
- Vehicle diagnostics laboratory
- Large-scale software and analysis laboratory
- Testing and evaluation of vehicles laboratory
- Aero-dynamic laboratory

At the School of Automotive Engineering, Tongji University has world-class facilities to integrate advanced batteries and fuel cells in vehicles and conduct basic and applied research for the automotive industry. These testing capabilities are comprehensive and cover research, testing, and evaluation. The equipment and capabilities are impressive.

The School of Automotive Engineering is involved in extensive research with lithium battery development companies, fuel cell development companies, and domestic and foreign automobile companies.

3.2.9.1 Automobile Companies

- Shanghai FCV Powertrain Co., Ltd.
- Volkswagen
- China Automobile Association
- China Automobile Dealers Association
- German engineering company, IAV GmbH (Ingeniergesellschaft Auto und Verkehr)
- EDS PLM Solutions
- Toyota Motor Co.
- Nissan
- General Motors

3.2.9.2 Battery Development Companies

- Huanyu Group
- CITIC Guoan Mengguli Corporation (MGL)
- Beijing Green Power Technology Co., Ltd.
- Beijing Oriental Polymer New Energy Co., Ltd.
- Leitian Green Electric Power Supply (Shenzhen) Co., Ltd.
- Thunder-Sky Battery Co.
- Suzhou Polylion Battery Co.

3.2.9.3 Fuel Cell Development Companies

- Shanghai FCV Powertrain Co., Ltd.
- Wan Xiaing FC Company
- Hang Zhou Energy Co.

The School of Automobile Engineering has seven fuel cell battery hybrid vehicles from three different developers to test and evaluate on the dynamometer and on the track. Each of these vehicles has a 15-kW polymer electrolyte membrane fuel cell stack and 10-kWh lithium-ion batteries. Faculty would like to have these vehicles ready for the 2008 Olympics. Argonne staff had an opportunity to ride in and drive two of these vehicles. The vehicles rode smoothly, and acceleration was as good as that of U.S.-manufactured vehicles. One of the vehicles had accumulated 20,140 km, and the other had 12,300 km. The lithium-ion batteries in both of these vehicles performed well and have a capacity of around 95% that of the original. These vehicles are small compared with U.S. vehicles — they weigh approximately 950 kg and carry four passengers.

Tongji University is very well connected with federal and state governments. The President, Dr. Gang Wan, is very well connected with the federal Department of Science and Technology. Recently, Dr. Wan became the Minister of MOST. He is also well associated with the state government and local automotive industry. Tongji receives a 15 million RMB ($2.00 million) grant from the federal government and 10 million RMB ($1.34 million) from the state government. It also receives several million RMB from automotive companies (the university did not want to disclose the names of those companies).

3.2.9.4 Other Activities at the School of Automobile Engineering

- A car, called *Chao Yue I*, which means "surpass," was built by Shanghai Fuel Cell Vehicle Power Train Co., under the direction from Tongji University, Shanghai Automotive Industry Corp., and other city departments. A total of $4.57 million RMB, from a central government grant, was used to develop the new hydrogen-based fuel cell vehicle engine. An additional $9 million RMB was offered to the company to continue further development of hydrogen fuel cell vehicles through 2007. Fuel-cell-powered cars are viewed as the most suitable vehicle for family use in China because they do not produce any harmful emissions — a great advantage as the country turns to vehicular mobility.

- The Beijing Oriental Company Group and Tongji University are building a new hydrogen refueling station in Shanghai. Tongji University is responsible for the overall management, while Shell, which is funding part of the project, is working with the school on the design, construction, maintenance, and operations of the station. The Beijing Oriental Company is providing the engineering and procurement services needed to deliver the packaged hydrogen compression, storage, dispensing system, and trucked-in compressed hydrogen for the station. This station is due for completion by the end of the year and will refuel 3 buses and 20 cars. The project is part of the Chinese Ministry of Science and Technology's national program for the commercialization of fuel cell vehicles in the country.

Tongji University is seriously interested in benchmarking advanced battery technology in the United States. University staff members have agreed to discuss this idea further with their battery development partners.

3.2.10 General Research Institute for Nonferrous Metals, Institute of Energy Materials and Technology Lab of Li-ion Battery (Beijing 100088)

The General Research Institute for Nonferrous Metals (GRINM), established in 1952, is the largest R&D institution in the field of the nonferrous metals industry in China. Dr. Hailing Tu, a well-known expert on semiconductor materials in China, is the president. Since its establishment, GRINM has carried out more than 5,000 projects. After 50 years of development, research areas have expanded to include microelectronic and photoelectronic materials, rare and precious metals materials, rare earth materials, energy technology and materials, special alloy powder and powder metallurgy materials, superconductor materials, nanotechnology and materials, infrared optical materials, nonferrous metals processing technology, advanced mineral processing and metallurgy, nonferrous metal composites, materials analysis, and testing. GRINM is a comprehensive research institute covering a wide range of research areas. One R&D area in which GRINM is involved is the development of lithium-ion battery technology for e-bikes, EVs, and HEVs, as well as for other portable applications, such as cell phones, camcorders, and various other electronic devices.

GRINM has also established a broad technical exchange, cooperation, and trading partnership with counterparts in more than 30 countries and regions. The institution is always ready to cooperate with partners around the world for mutual growth and development.

GRINM is conducting basic research on the materials needs and requirements for high-energy and high-power lithium-ion battery technology. It has focused on nanotechnology and $LiMn_2O_4$ materials for the cathode, graphite for the anode, and PC+DC+DMC+1m Li P F6 liquid electrolyte and PP/PE/PP separator for the development of a lithium-ion battery cell. GRINM developed all materials in house except for the separator, which it imports from Japan and the United States.

3.2.10.1 GRINM’s Lithium-Ion Cells

GRINM has designed several lithium-ion cells; some properties and data are given in Table 14.

In some test results, GRINM showed that ampere-hour capacity dropped to 80% at the end of 800 cycles and to 60% at the end of 1,200 cycles. GRINM has fabricated 1,200 cells in each of the above categories.

At present, GRINM is working with Weifang Jade Bird Huanguang Battery Co., Ltd. This battery company will manufacture cells and batteries for EV and HEV applications, and these batteries will be integrated in the First Automotive Factory of China’s electric and hybrid vehicles. GRINM has 10 e-bikes, two EVs, and two hybrid vehicles that are being evaluated.

TABLE 14 Properties and Data from GRINM Lithium-Ion Batteries

	Battery Model					
Parameter	HP-40	HP-30	HP-25	HP-17	HP-10	HP-8
Nominal Voltage	3.6	3.8	3.8	3.8	3.8	3.8
Average Capacity (A•h)	40	30	25	17	10	8
Diameter × Height (mm)	Dia 56 × 258	Dia 56 × 228	Dia 47 × 341	Dia 47 × 288	Dia 47 × 180	Dia 47 × 165
Typical Weight (kg)	1.55	1.48	1.17	0.98	0.60	0.45
Volume (dm^3)	0.64	0.60	0.59	0.50	0.31	0.28
Specific Energy (Wh/kg)	110	80	85	70	85	65
Specific Power (W/kg) (10 s/50% DOD)	898	1,048	1,082	1,320	1,500	1,450
Imax Max Discharge Current (A)	400	300	250	270	200	200
Voltage Limits						
Charge (V)	4.2	4.2	4.2	4.2	4.2	4.2
Discharge (V)	2.8	3.2	3.2	3.2	3.2	3.2

The institute receives 5 million RMB per year ($0.67 million/yr) in grants from the federal government. It has 2,000 employees, and 38 are working on lithium-ion batteries. The Institute has seven patents, primarily on materials and cell design.

3.2.10.2 Other Information on GRINM

GRINM has an excellent record in terms of cooperating with other countries. The institute has shown very strong interest in a cooperative effort to benchmark its technology in the United States. Also, GRINM is interested in cooperating with other organizations to develop a lithium-ion battery for vehicular applications.

3.2.11 Beijing Institute of Technology
BIT EV Center of Engineering and Technology
(Beijing 100081)

The Chinese government has designated Beijing Institute of Technology (BIT) as the Center of Excellence for the EV Bus Development Program. BIT is the most prestigious institute in China. It has excellent laboratories with the most modern equipment for testing and evaluation of each component of an electric bus. Also, BIT can evaluate electric buses and passenger cars on a dynamometer and on controlled tracks.

A typical lithium-ion battery for a large-bus application consists of 108 cells in series and four banks in parallel to provide 400-A•h capacity with nominal 388 V. They charge cells to 4.2 V and discharge to less than 3 V.

3.2.11.1 Bus Manufacturing and Related Technology

BIT is working on bus manufacturing with the following companies:

- Beijing Beifang Huade Niopolan Bus Company, Ltd.
- Jinghua Bus Company, Ltd.
- BIT Clean Electric Vehicle Company, Ltd.

The technology that is being used for electric buses is described below.

Rare-earth charging flux permanent magnet direct current motor:

- Rare-earth permanent magnet and increasing magnetic winding combined excitation

- Rotor-adopting no-groove structure

- Increasing magnetic winding links to re-flowing current loop to auto-decrease magnetic field

Controller of rare-earth charging flux permanent magnet direct current motor:

- High-frequency PWM control
- Auto-decrease to realize the modulation
- Current of close loop controller
- Recovery of regenerative breaking energy

System parameters:

- System efficiency >92%, with 80% high-efficiency area for 84.4% of the time
- 75 kW/125 kW; maximum moment of system at 1,200 Nm

- Line-control two-speed gear box

Specifications for electric ultra-low-floor bus:

- Lithium-ion battery, 388.8 V @400 A•h
- Power driving system: three-phase, asynchronous alternating-current motor, 175 kW
- Wheelbase (mm): 5,800
- Wheel span (front/rear) (mm): 2,340/3,440
- Curb mass/full-load mass (kg): 12,930/16,000
- Max velocity (km/h): 91
- Driving range (40 km/h): 210 km
- 0–50 km/h acceleration time in s: 20.7
- 30 km/h braking distance in m: 8.2

BIT has 12 electric buses that are being evaluated. These buses will be put in use during the 2008 Beijing Olympics. Nearly all of the laboratory's equipment to evaluate electric buses has been imported from Germany, Japan, and the United States.

BIT is 100% supported by the Chinese federal and state governments. BTI has several patents on electric drive trains for buses, as well as for passenger vehicles.

3.2.11.2 Other Information

BTI is interested in working with U.S. companies on electric buses, as well as on component technologies.

3.3 LITHIUM-ION BATTERY MANUFACTURING IN CHINA

The production and manufacturing of lithium-ion batteries has expanded enormously in the past two to three years. These batteries are widely used in consumer electronics devices, such as cellular phones, camcorders, and portable computers. This market is growing so fast that it is only second behind the development of information technology. Battery manufacturing ranges from manual operations to full automation. Labor cost also plays a significant role in manufacturing lithium-ion batteries. Currently, China has between 275,000 and 325,000 workers in the battery industry. Labor costs in China are very low compared with labor costs in the west and Japan. Approximately 435 batteries companies in China produce batteries. The total output in 2006 was 78.7 billion Yuan ($1.06 billion).

The Chinese government aggressively supports the development of new types of batteries, such as lithium batteries, fuel batteries (fuel cell), and solar batteries. China's 10th five-year plan and 863 Program listed the lithium battery and related key materials as an important research project in the new material field, which greatly promoted the research and development of the lithium battery. To realize the goal of holding a "Green Olympics" in Beijing and to welcome the Shanghai World Expos in 2010, Beijing and Shanghai launched a series of regulations, policies, and measures to promote applications of the battery for automobiles to reduce exhaust emissions and protect the environment. In October 2003, the National Development and Reform Commission, Ministry of Science and Technology, developed a solar energy R&D plan for implementation in the next seven years — the "Bright Project" of the National Development and Reform Commission will raise 10 billion Yuan ($1.35 billion) to promote applications for solar power generating technologies, and the installed capacity of China's solar power generating system is expected to reach 300 MW by 2009.

Because of the reduced use of NiMH batteries and nickel-cadmium batteries and the popularization of mobile electronic products such as mobile phones, digital computers, digital video, and personal data acquisition, the use of lithium-ion batteries surged, and the potential of these batteries in the rechargeable battery field is significant. Worldwide, the output of lithium-ion batteries surpassed that of nickel-cadmium batteries in 2003, and the trend continued in 2004.

The number of shipments of mobile phones and laptops continued to increase in recent years, although the growth of mobile phones slowed down in 2005. The growth, however, of laptops, DCs, and DVs enabled the rate of growth of the lithium-ion battery industry to remain high. The compound growth rate of world production of the lithium ion battery reached 23% during 2004–2006; the compound growth rate of sales revenue will reach 12.3%, according to MOST. During 2007–2010, the lithium-ion battery industry will enter a stable growth period, during which the rate of growth in production is expected to be 9.85%, and the compound growth rate of sales revenue is expected to reach 5.85%, according to the Tianjin Institute of Power Sources.

The lithium polymer battery was mass-produced in 1999, and the growth rate of these batteries is always higher than that of the lithium-ion battery. The lithium polymer battery accounted for 7%, 8%, and 10%, respectively, of the market share for lithium-ion batteries in 2002, 2003, and 2004.

R&D trends of the lithium-ion battery industry include further increases in energy density; safer environmental performance; lower manufacturing cost; development of new electrode materials; development of lighter, thinner batteries; and development of improved manufacturing techniques.

3.4 JOINT VENTURES AND PARTNERSHIPS

Western and Japanese companies are setting up joint ventures and/or partnerships with Chinese battery companies because of the widespread incentives available to Chinese companies. Chinese companies receive more incentives if they are producing batteries for export. At present, Chinese companies are providing batteries for electronic and portable applications worldwide. Because the initial investment to produce lithium-ion batteries is very high, producing batteries in China is cost-effective.

The following paragraphs briefly describe the relationships of various western and Japanese companies with Chinese battery companies for production of lithium-ion batteries.

Shenzhen BAK Battery Co., Ltd., has signed manufacturing agreements with (1) Lenovo Group, Ltd., for portable and tabletop personal computers and cell phone markets and (2) A123 Systems for high-power lithium-ion battery technology based on patented nanotechnology. The Strategic Cooperation Agreement with Lenovo calls for both companies to jointly contribute and share resources to further product-development efforts. The company has been a supplier of lithium-ion battery cells for Lenovo's cell phones since last year (2005). This Agreement was signed to expand the current relationship and facilitate the development of new battery sizes for Lenovo in the portable and notebook PC markets. Shenzhen BAK Battery Co., Ltd., and A123 have collaborated since early 2005 to design, develop, and implement an advanced mass-production line to exclusively manufacture first products for A123. The A123 Systems nano-phosphate lithium-ion technology is based on patented technology developed at the Massachusetts Institute of Technology (MIT). The A123 high-power batteries will be used in a variety of applications, including power tools, medical devices, and hybrid electric vehicles. In 2005, Shenzhen BAK Battery Co., Ltd., raised approximately $60 million that enabled a significant expansion of manufacturing facilities, which increased production from 15 million to 22 million batteries per month. Shenzhen BAK Battery Co., Ltd., also established volume production capability for lithium-polymer battery cells and constructed a production line for a new high-power battery cell initially directed toward the cordless power tool market and other applications. Shenzhen BAK Battery Co., Ltd., has successfully launched its first automated cylindrical lithium-ion battery cell production line. The new production line employs advanced technologies and automation for the manufacture of consistently high-quality cylindrical cells for notebook computers. The monthly production capacity has reached two million units.

ARIA Investment Partners II, a fund managed by CLSA Private Equity Management, Ltd., has invested $10 million in China's Great Speed Enterprises, Ltd., a holding company of Scud (Fujian) Electronics Co., Ltd. Scud Electronics is one of the largest makers of lithium-ion batteries for mobile phones in China. Its retail distribution network has more than 200 wholesalers, which manage over 100,000 points of sales and cover all the provinces and large cities across China.

Advanced Battery Technologies, Inc. (ABAT), a subsidiary of Beijing Tonghe Jiye Trade, Ltd. (Tonghe Jiye), has received an order for 100,000 mine-use lamps using ABAT's 3.7-V, 9-A•h lithium-ion polymer batteries. This order has a total contract value of 24.8 million RMB (about $3 million). The Chinese government has given ABAT a safety certificate that allows the production of mine-use lamps using this battery. Mine-use lamps have an annual market of about $120 million in China. ABAT is resuming production in its newly built factory in Heilongjiang, China, with three production lines. The new factory has a daily lithium-ion polymer battery production capacity of 50,000 A•h per 8-h shift, which is 10 times the capacity of the preexisting plant. The old facility is being converted into an R&D laboratory. The company's products include rechargeable lithium-ion polymer batteries for electric automobiles, motorcycles, mine-use lamps, notebook computers, walkie-talkies, and other personal electronic devices. ABAT has filed a patent application for its nano-lithium-ion battery system. ABAT has been developing a new polymer lithium-ion battery by using lithium titanate spinel nanomaterials provided by Altair Nanotechnologies, Inc. ABAT has developed a method for incorporating the nanomaterials into its battery. The company has shipped its first group of new nano-lithium-ion batteries to its U.S. customer. The nano-lithium-ion batteries use lithium titanate spinel electrode nanomaterials provided by Altair Nanotechnologies, Inc.

Fengfan Storage Battery Co., Ltd., and the Hongwen Group jointly developed a lead-acid production facility in Guizhi, Tanshang City, of North China's Hebei Province, with an estimated investment of one billion yuan ($121 million). Fengfan contributed 51% of the investment, and Hongwen contributed the remaining 49%. The Fengfan-Hongwen storage battery project will mainly produce batteries for use in automobiles. This joint venture plans to develop lithium-ion battery technology for portable and automobile applications.

Inco has officially opened its joint venture nickel foam plant — Inco Advanced Technology Materials (Dalian) Ltd. — in Dalian, China. Nickel foam is a specialty nickel product used in NiCd and NiMH rechargeable batteries, including batteries used as a power source for hybrid automobiles.

According to *China Customs* statistics, mainland China's battery production volume currently represents at least 25% of the global supply. Some industry sources say the percentage may even be as high as 50%. The China Industrial Association of Power Sources reported that 28 billion units of batteries were produced in mainland China in 2004. The 151 battery makers included in their report represent about 70% of mainland China's production capability. These have an individual output of between 5,000 units and 170 million units monthly, with about 96% of them operating at 70% of production capacity. Most of the battery makers are located in Guangdong, Shanghai, Zhejiang, Jiangsu, Tianjin, Shenyang, Fujian, and Harbin. Other findings in this report include:

1. Mainland China is the world's largest supplier of alkaline batteries, with output of primary cells reaching 22 billion units in 2004. Production was increased by 10% in 2005.

2. Over 800 million units of NiMH batteries were manufactured in mainland China in 2004. This is about 40% of the global supply in 2004. Exports of NiMH batteries totaled 675 million units, valued at $442 million in 2004. About 60 new companies included NiMH rechargeable batteries in their product lines in 2005.

3. About 30% of the world's requirement for sealed lead-acid batteries is supplied by mainland China. Shipments of sealed lead-acid batteries totaled about 107 million units in 2004, which was an increase of 25% from 2003. In 2005 and 2006, electric vehicles, uninterrupted power sources, emergency lighting, security systems, and industrial applications drove the demand for sealed lead-acid batteries. Mainland China's production of NiCd batteries hit 1 billion units in 2004. Production is expected to grow by 5–10% in the next five years. Exports of NiCd reached 826 million units in 2004, valued at $411 million.

Ovonic Battery Company, Inc., has entered into a patent license agreement in connection with its proprietary NiMH battery technology with *Hunan Corun Hi-Tech Co., Ltd.*, of the PRC. Under the consumer battery license grant, Hunan Corun has a royalty-bearing, nonexclusive right to make, use, and sell NiMH batteries for consumer and nonpropulsion applications. Hunan Corun was founded in 2001. Its factory is located in the Chao Yang economic development zone in YiYang, Hunan, within the PRC. Hunan Corun manufactures a wide range of NiMH products, has approximately 3,000 employees, and produces a variety of battery chemistries. Ovonic also entered into a patent license agreement in connection with its proprietary NiMH battery technology with *Zhejiang Kan Battery Co., Ltd.*, of the PRC. Under the consumer battery license grant, Zhejiang Kan has a royalty-bearing, nonexclusive right to make, use, and sell NiMH batteries for consumer and nonpropulsion applications. Zhejiang Kan was founded in 1993 and is technically affiliated with *Zhejiang University*. Zhejiang Kan's factory is located in Suichang, Zhejiang, and its marketing office is in Hong Kong. Additionally, Ovonic has entered into a patent license agreement in connection with its proprietary NiMH battery technology with *L&K Battery Technology Co., Ltd.*, of the PRC. Under the consumer battery license grant, L&K Battery has a royalty-bearing, nonexclusive right to make, use, and sell NiMH batteries for consumer nonpropulsion applications.

Suntech Power has signed a letter of intent with Wanzhou District of Chongqing Municipality to construct a battery production base involving an investment of 200 million yuan ($24.9 million). Its local partner will be *Wanguang Power Source*, an old state-owned enterprise. The state-owned Assets Supervision and Administration Commission of Wanzhou District is negotiating with Suntech on acquisition details. Wanguang Power Source makes storage batteries used in automobiles and motorcycles, with annual output valued at 180 million yuan ($24.3 million). It is 51% held by Wanguang Industrial Group, 29.9% by Lifan, and 16.63% by Chongqing Xinmiao Technology Investment Company. Low labor cost is a factor that affects Suntech's domestic expansion scheme. Suntech, which is headquartered in China's eastern Wuxi City, is the sixth largest solar energy company in the world, with an annual battery output of 120 MW. Its products are mainly for export. Chongqing is a leading automobile- and motorcycle-manufacturing base in China, which also is an important reason for Suntech's plan to build a battery production base in the city.

ZAP is using ABAT's lithium-ion polymer batteries in its electric vehicles. Under the first phase of a new agreement, ABAT will retrofit a range of ZAP EVs with its lithium-ion polymer batteries and chargers. The initial testing shows that the ABAT batteries are increasing the run time of ZAP's vehicles by three times over that of lead-acid batteries. The threefold increase in energy density of the lithium polymer batteries could enable a similar threefold increase in transportation range for comparable-weight batteries, enabling ZAP's vehicles to achieve a significantly increased driving range between electric recharges.

Degussa AG, Düsseldorf, is starting additional electrode production for large-volume lithium-ion batteries at the Li-Tech GmbH (SK Group) site in Kamenz/Dresden. The first expansion stage saw anode and cathode production come onstream in the fourth quarter of 2006. Degussa has production capacities in China through the joint venture *Degussa-ENAX (Anqiu) Power Lion Co. Ltd.* The German site is targeting large-volume energy storage applications, such as batteries for hybrid vehicles. With its ceramic membrane, Separion®, the specialty chemicals company had positioned itself at an early stage in the promising market for lithium-ion batteries. According to Degussa, the global market for lithium-ion battery materials experienced double-digit growth in 2004 and currently amounts to more than $1.2 billion. Degussa expects the market volume to increase to around 4 billion by 2015.

Ultralife Batteries, Inc., has completed the acquisition of ABLE New Energy Co., Ltd., which is located in Shenzhen, China. Established in 2003, ABLE produces primarily Li-MnO_2 and Li-$SOCl_2$ batteries for a wide range of applications worldwide, including utility meters, security systems, tire pressure sensors, medical devices, automotive electronics, and memory backup, among many others.

3.5 GOVERNMENT POLICIES

The Government policies provide tax and investment incentives for the following areas of advanced technologies research, development, and manufacturing:

Guidance on previously developed high-tech industrialized key fields: The National Development and Reform Commission, Ministry of Science and Technology, Ministry of Commerce of PRC, published Guidance on Prior-Developed High-Tech Industrialized Key Fields in April 2004. This content is associated with the battery industry and includes new types of batteries/power supplies such as lithium-ion cells and batteries, portable photovoltaic (PV) power supply systems, and a new type of solar film battery. The federal government provides additional incentives for the development of these technologies. This includes subsidies for hiring recent graduates and some tax break.

Materials with special functions: This category includes energy conversion and energy storage materials, including a hydrogen storage alloy and a hydrogen storage container, solar batteries, high-performance rechargeable lithium batteries, and a new type of capacitor.

Fuel battery (fuel cell): Fuel cells use hydrogen or rich-hydrogen gas as fuel and oxygen as oxidant; it converts chemical energy into electricity. This energy conversion is efficient and environmentally friendly because almost no nitrogen oxide or sulfur oxide is discharged. The key technologies included in the recent industrialization are battery materials; 1-kW–100-kW proton-exchange membrane fuel cells and electrical catalysts; electrodes; Nafionpolytetrafluoroethylene compound films; bipolar plates; proton-exchange membrane fuel cells; and direct-methanol, molten carbonate, and solid oxide fuel cells.

New energy and renewable energy: China possesses rich renewable energy resources. Properly developed and promoted, renewable clean energy (such as bio-energy, wind energy, solar energy, hydrogen energy, and geothermal energy) has great potential to reduce pollution and improve China's energy structure. Its recent industrialization plan also includes: biomass gasification; electricity-generating and air-feeding technology; biomass liquid fuel technology; design, manufacture, and production of a 750-kW wind-power generator set and related components; a megawatt wind-power generator set and related components; high-efficiency, low-cost solar PV cells; medium- and high-temperature solar-energy-generating equipment; a ground-source heat pump; and a heating, air-conditioning, and hot-water combined supply system.

3.5.1 Renewable Energy Law

On February 28, 2005, the Renewable Energy Law of the People's Republic of China was passed during the 14th session of the 10th National People's Congress Standing Committee. This law, effective as of January 1, 2006, will greatly promote the development and use of renewable energy, the increase in energy supply options, the optimization of energy structure, the energy security guarantees, and the environmental protection and sustainable development of China. The Renewable Energy Law defines the term "renewable energy" as non-fossil energy sources, which include wind, solar energy, hydropower, biomass, geothermal energy, and ocean energy.

3.5.2 Government Plan

The rechargeable lithium-ion battery is a new and important technology in the energy field and is strongly supported by the Chinese government. Since the initiation of China's 863 Program in 1987, the Ministry of Science and Technology organized the research and development of the key materials and technologies of the NiMH battery and lithium-ion battery that shaped a large industrial-scale role for Chinese companies worldwide.

During the period of the 10th five-year-plan, China could realize the batch production and industrialization of hybrid electric automobile and build power batteries and industrial bases for related materials. Recently, the National Development and Reform Commission of China decided to support the construction of a base from which to demonstrate the industrialization of lithium-ion batteries to further promote the development of lithium-ion battery.

Compared with other countries, China still lacks the ability to update technology rapidly and introduce innovations. The "973" Plan of the Ministry of Science and Technology has been approved to promote the development of green technologies and accelerate the development of the energy structures that are green and renewable. Establishing this green rechargeable battery technology program will emphasize innovative research in battery materials, new systems of green rechargeable batteries, and related technologies.

3.5.3 Relevant Standards

The national standards of the battery industry are summarized in Table 15.

TABLE 15 Guobiao (GB) Standards of the Battery Industry

GB Number	Title/Name
GB/T 2297-1989	Terminology for solar photovoltaic energy system
GB/T 2900.11-1988	Terminology of (secondary) cell or battery
GB/T 5008.1-1991	Lead-acid starter batteries — Technical conditions
GB/T 5008.2-1991	Lead-acid starter batteries — Varieties and specifications
GB/T 5008.3-1991	Lead-acid starter batteries — Dimension and marking of terminals
GB/T 6495.1-1996	Photovoltaic devices — Part 1: Measurement of photovoltaic current-voltage characteristics
GB/T 6495.2-1996	Photovoltaic devices — Part 2: Requirements for reference solar cells
GB/T 6495.3-1996	Photovoltaic devices — Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data
GB/T 6495.4-1996	Procedures for temperature and irradiance corrections to measured I-V characteristics of crystalline silicon photovoltaic devices, Battery Industry in China, 2005
GB/T 7169-1987	Designation of alkaline secondary cell
GB/T 7260-1987	Uninterruptible power systems
GB/T 7403.1-1996	Lead-acid traction batteries
GB/T 7403.2-1987	Lead-acid traction batteries — Product types and specifications
GB/T 7404-1987	Lead-acid batteries for diesel locomotives
GB/T 8897-1996	Primary batteries: General
GB/T 9368-1988	Nickel-cadmium alkaline secondary cells
GB/T 9369-1988	Nickel-cadmium alkaline secondary batteries
GB/T 10077-1988	Maximum outside size and capacity series for lithium batteries
GB/T 10978.2-1989	Lead-acid batteries for special type explosion-proof power unit in coal mines — Product types and specifications
GB/T 11009-1989	Measuring methods of spectral response for solar cells
GB/T 11010-1989	Spectrum standard solar cell
GB/T 11011-1989	General rules for measurements of electrical characteristics of amorphous silicon solar cells
GB/T 11013-1996	Alkaline secondary cells and batteries — Sealed nickel-cadmium cylindrical rechargeable single cells
GB/T 12632-1990	General specification of single silicon solar cells

TABLE 15 (Cont.)

GB Number	Title/Name
GB/T 12637-1990	General specification for solar simulator
GB/T 12724-1991	General specification for silver-zinc rechargeable cells
GB/T 12725-1991	General specification for alkaline nickel-iron rechargeable batteries
GB/T 13281-1991	Lead-acid batteries used for passenger trains
GB/T 13337.1-1991	Stationary acid spray-proof lead-acid batteries — Technical conditions
GB/T 13337.2-1991	Stationary acid spray-proof lead-acid batteries — Capacity specifications and size
GB/T 13422-1992	Power semiconductor converters — Electrical test methods
GB/T 14008-1992	General specification for sea-use solar cell modules
GB/T 15100-1994	General specification for alkaline nickel-metal hydride cylindrical sealed rechargeable batteries
GB/T 15142-1994	General specification for nickel-cadmium alkaline rechargeable single cells
GB/T 6495.5-1997	Photovoltaic devices — Part 5: Determination of the equivalent cell temperature of photovoltaic (PV) devices by the open-circuit voltage method
GB/T 17571-1998	Alkaline secondary cells and sealed-nickel batteries — Cadmium rechargeable monobloc batteries in button cell design
GB 8897.2-2005	Primary battery — Part 2: Sizes and technical conditions

A new battery standard, GB8897.2-2005, was issued in January 2005 and became effective on August 1, 2005, replacing GB/T7112-1998. The original standards of the light industry, QB/T528-1966, QB/T1186-1991, and QB/T1732-1993, were abolished at the same time. In 2005, the product quality testing standard of the battery industry was changed to GB8897.2-2005.

The Standardization Administration of China will draw new standards for cell-phone use of lithium-ion battery to replace the existing ones. At the national standard coordination meeting held in Qingdao in 2004, Aucma New Energy Company was chosen to take charge of the development of new standards for lithium-ion batteries used in cell-phones. The draft work started in July 2004, which clearly prescribes the capacity, cycling life-span, and safety of batteries used in mobile phones.

3.5.4 Regulatory Steps to Promote Cleaner Transport

In the new Five-Year Plan (2006–2010), the Chinese government outlines steps to boost efficiency and reduce pollution. A number of clear targets for increasing energy efficiency are set (e.g., to increase total energy efficiency by 20% and achieve an energy mix of at least 20% renewable energy by 2020). The Chinese government also introduces clear policies:

- As of April 1, 2006, buyers of new, big cars paid 20% more in sales tax, and buyers of smaller cars paid 1% less in sales tax.
- By the end of 2006, the parking fees in central Beijing doubled.
- During 2006, the price of gasoline for end consumers increased by about 20% (because older subsidies had been lifted).
- Starting December 2005, tighter vehicle standards were approved.

3.5.5 Example of Income Taxes and Incentives

Under applicable income tax laws and regulations, an enterprise ABC (not a real name of a company) located in Shenzhen, including the district in which operations are located, is subject to a 15% enterprise income tax. Further, according to PRC laws and regulations, foreign-invested manufacturing enterprises are entitled to, starting from their first profitable year, a two-year exemption from enterprise income tax, followed by a three-year 50% reduction in the enterprise income tax rate. The PRC subsidiaries are entitled to a two-year exemption from enterprise income tax and a reduced enterprise income tax rate of 7.5% for the three years following the first profitable year. As such, for the first two calendar years, ABC enterprise was exempted from any income tax. For the following two years, this enterprise is subject to the income tax rate of 7.5%. Some preferential tax treatment is also applicable to this enterprise, and the enterprise is fully exempt from any income tax during a tax holiday. (A tax holiday is a designated period — the month of June each year — during which companies do not pay income tax on equipment purchases or any other incurred business expenses.)

In addition, due to the additional capital invested in the ABC enterprise, it was granted a lower income tax rate of 1.7% for two years. Furthermore, to encourage foreign investors to introduce advanced technologies in China, the government of the PRC has offered additional tax incentives to enterprises that are classified as a foreign-invested enterprise with advanced technologies. If the enterprise qualifies for this designation, then it pays 1.7% in taxes for an additional three years. It can then renew this status and pay low income taxes. As a result, as long as ABC maintains this designation, it may apply to the tax authority to extend its current reduced tax rate of 1.7% for another three years.

3.6 GOVERNMENT POLICIES AND HEV STANDARDS

The HEV-pro policy has been clearly included in the new China Auto Industry Policy. The R&D and industrialization of HEVs have been listed as a major component of government funding for technology development in China. Also, the related HEV standards will be recommended and adopted by auto makers in China:

- Test methods for energy consumption of light-duty hybrid EVs
- Measurement methods for emissions from light-duty hybrid vehicles
- Program for approving the engineering evaluation of HEVs
- Programs for testing the comprehensive performance of HEVs
- Safety specifications for HEVs
- Method for testing the power performance of HEVs
- Technical specifications of the motor and controller for EVs
- Method for testing the motor and controller for EVs

4 SUMMARY AND RECOMMENDATIONS

The lithium-ion battery offers very high power on charge and discharge and further improvements — desirably in power at low temperature — may be possible. The main challenge for this technology — besides cost reduction — is to achieve acceptable operating life, particularly at 40°C. Battery companies, as well as R&D organizations worldwide, are making major efforts to mitigate the relatively rapid fading of the $LiMn_2O_4$ lithium-ion battery at elevated temperatures. However, the degree of improvement that will be achieved is difficult to anticipate.

The basic chemistry and design of lithium-ion HEV cells are quite similar to those of small consumer cells, which suggests that the basic manufacturing processes for HEV batteries should be well understood. The manufacture of lithium-ion cells is known to require a higher level of process control and precision than most other types of battery manufacturing, and, as a result, scrap rates tend to be higher. Most, if not all, producers of small lithium-ion batteries have experienced product recalls and/or production shutdowns as result of reliability issues and/or safety incidents. Extrapolating this experience to the much larger HEV cell with thinner electrodes, it seems likely that scaling up the production of HEV cells from the current early pilot level will be slow and costly. If lithium-ion HEV batteries are to become commercially viable, operating life and abuse tolerance issues will need to be resolved first, and then the unit cost of the technology will need to be reduced, at least to the levels projected for NiMH batteries.

Because the 2008 Olympics will be held in Beijing, the Chinese government designated lithium-ion battery technology as a strategic technology for the development and manufacturing of portable and vehicular applications. As a result of this designation, foreign companies were attracted to work with Chinese companies to form joint ventures and/or partnerships, since the potential size of Chinese markets for portable electronics and vehicular applications is significant.

The following recommendations are made:

1. A DOE Program Official(s), along with experts, should visit China to study its battery technology industry firsthand and to make arrangements for benchmarking Chinese battery technology in the United States. Chinese companies have expressed a strong interest in making battery technology available for benchmarking. The timing is right, and interest in working with the United States is very strong.

2. The DOE and the Tianjin Institute of Power Sources should work together to set up a battery workshop in China and invite U.S. industry to participate. This effort will help the U.S. industry to work with its counterparts to more rapidly develop advanced, reliable, low-cost lithium-ion batteries.

3. The Chinese universities and institutions have shown broad interest in cooperation. DOE should pursue such cooperation as a way to learn more about Chinese battery technology.

4. CITIC Guoan MGL; MGL New Energy Technology Co., Ltd.; Green Power Co.; Tianjin Lintian Double-Cycle Tech. Co.; Suzhou Phylion Battery Co., Ltd.; Tianjin Lishen Battery Joint-Stock Co., Ltd.; and Tongji University have expressed interest in having their staff do postdoctoral fellowships in the United States. This is an opportunity for national laboratories and the industry to build stronger relationships with Chinese companies and institutions.

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The Administrative Commission of Wuhan East Lake High
Technology Development Zone
#450 Luoyu Rd. Wuhan
CN, Hubei 430079
China
www.chinaov.org

Alibaba.Com
6/F, Chuangye Mansion
East Software Park, 99 Huaxing Road
Hangzhou 310012, China
http://www.alibaba.com/companies/1009/Storage_Batteries_Secondary_Batteries.html

Battery University
Cadex Electronics
www.batteryuniversity.com

China Electric Vehicles
www.chinaev.com.cn

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Electric Drive Transportation Association
1101 Vermont Ave. NW, Suite 401
Washington, D.C., 20005
www.electricdrive.org

EVS21.org
http://www.evs21.org/rubrique42.html

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http://www.frost.com/prod/servlet/report-brochure.pag?id=D283-01-00-00-00

Global Sources
c/o Media Data Systems Pte., Ltd.
Raffles City
PO Box 0203, Singapore 911707
http://www.globalsources.com/gsol/I/Lithium-ion-manufacturers/b/2000000003844/3000000181565/22761.htm

Global Sources
c/o Media Data Systems Pte., Ltd.
Raffles City
PO Box 0203, Singapore 911707
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Guangzhou Langging Electric Vehicle Co., Ltd.
Langqing Industrial Park No 1 Langqing Road
Taishi Village Dongchong Town, Panyu District
Guangzhou, P.R. of China
http://www.langqing.com

Hybrid Cars
http://www.hybridcars.com/lithium-ion-hybrid-batteries.html

Institute of Electrical Engineering
Academy of Sciences in the Czech Republic
Dolejskova 5, 182 02 Prague 8, Czech Republic
www.iee.cas.cz

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MINDBRANCH
131 Ashland Street
North Adams, MA 01247
http://www.mindbranch.com/listing/product/R2-938.html

NERAC
One Technology Drive
Tolland, CT 06084
http://www.nerac.com/samples/lithium_batteries.htm

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SL Power Electronics™
Headquarters
6050 King Drive
Ventura, CA 93003
www.Slpower.com

Society of Automotive Engineers of China
www.sae-china.org

Source Guides
http://energy.sourceguides.com/businesses/byP/ev/hybridev/byB/wholesale/supplier.shtml

Suzhou Phylion Battery Co., Ltd.
No. 81, Xiangyang Road,
Suzhou New District, Jiangsu 215011
www.xingheng.com.cn

Thunder Sky Energy Group Limited
Lisonglang Village, Gongming Town, Bao'an Dist., Shenzhen, P.R.C
Post code: 5181016
www.Thunder-sky.com

Tianjin Bluesky Double-Cycle Tech. Co., Ltd.
13, Road 4, Haitai Development, Huayuan
Industrial Park of Tianjin
New Tech Industrial Zone, 300384
www.tjshuanghuan.com

Tianjin Peace Bay Power Sources Co., Ltd.
No. 15 Kaihua Road, Huayuan Park
Hi-tech Industry Area, 300191
www.peacebay.com

Zhongyin (Ningbo) Battery Co., Ltd.
Ningbo Battery & Electrical Appliance I/E Co., Ltd.
99 Dahetou St., Duantang, Ningbo, China
http://www.sonluk.com/pro,lithium,round.htm.htm

APPENDIX A: ORGANIZATIONS REPRESENTED IN INTERVIEWS

LITHIUM-ION BATTERY COMPANIES AND INSTITUTIONS IN CHINA

1. Dr. Tian Guangyu, Professor
   Tsinghua University
   Department of Automotive Engineering
   Beijing, 100084

2. Dr. Lin Chengtao, Professor
   Tsinghua University
   Department of Automotive Engineering
   Beijing, 100084

3. Mr. Wei Feng, Manager
   Division of International Cooperation & Trade Promotion
   China Electrotechnical Society
   Beijing 100823

4. Dr. Sun, Li, Secretary General
   Chinese Electrotechnical Society Electric Vehicle Institution
   North China University of Technology
   Beijing 100041

5. Dr. Liqing Sun, Professor
   School of Mechanical Engineering & Vehicular Engineering
   Deputy Secretary General, Special Committee of Electric Vehicles
   China Electrotechnical Society
   Beijing 100081

6. Dr. Zhou Sigang, Professor
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   Executive Deputy Secretary General
   Beijing 100823

7. Li Yongwei, Administrative Vice Director
   Research Institute
   CITIC Guoan MGL
   MGL New Energy Technology Co., Ltd.
   Beijing 102200

8. Wu Ningning, Vice Director
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   CITIC Guoan MGL
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9. Yuan Chun Huai
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   Beijing100086

10. Dr. Wang Haoran
    Beijing Green Power Technology Co., Ltd.
    Beijing100086

11. Dr. Zhang Bao Wen, Senior Researcher
    Beijing Green Power Technology Co., Ltd.
    Beijing100086

12. Dr. Wang Ji Qiang, Vice Chief Engineer and Professor
    Tianjin Institute of Power Sources
    Tianjin 300381

13. Ms. Yu Bing, Engineer/Object Manager
    Testing Center of Chemical & Physical Power Sources
    Ministry of Information Industry
    Testing Center of Electric Vehicle Battery of National 863 Project
    Tianjin 300381

14. Dr. Xu Gang, Vice-President
    Tianjin Lishen Battery Joint-Stock Co., Ltd.
    Tianjin 300384

15. Wang Guo Ji, Vice Manager
    Tianjin Lantian Double-Cycle Tech. Co., Ltd.
    Tianjin 300384

16. Zhao Chunming, Master Senior Engineer
    China Automotive Technology & Research Center
    Tianjin 300162

17. Dr. Wu Xiao Dong, Tech. Dept. Manager
    Suzhou Phylion Battery Co., Ltd.
    Jiangsu 215011

18. Dr. Zhang Lu, Tech. Dept. Testing Center
Suzhou Phylion Battery Co., Ltd.
Jiangsu 215011

19. Xuezhe Wei, Professor
School of Automobile Engineering
Tongji University
Shanghai FCV Powertrain Co., Ltd.
Shanghai 201804

20. Wei Yang
School of Automobile Engineering
Tongji University
Shanghai FCV Powertrain Co., Ltd.
Shanghai 201804

21. Dr. Zhang Xiangjun, Director
General Research Institute for Nonferrous Metals
Institute of Energy Materials and Technology Lab of Li-ion Battery
Beijing 100088

22. Jin Wei Hua, Senior Engineer
General Research Institute for Nonferrous Metals
Division of Mineral Resources, Metallurgy & Materials
Beijing 100088

23. Wu Guoliang, Vice General Manager
Weifang Jade Bird Huanguang Battery Co., Ltd.
Weifang, Shandong 261031

24. Dr. Zhang Jun, Professor
Beijing Institute of Technology
BTI EV Center of Engineering and Technology
Beijing 100081

25. Dr. He Hong-Wen, Professor
Beijing Institute of Technology
BTI EV Center of Engineering and Technology
Beijing 100081

26. Dr. Wang Zhen-po, Professor
Beijing Institute of Technology
BTI EV Center of Engineering and Technology
Beijing 100081

27. Jinhua Zhang, Vice President
    China Automotive Technology & Research Center
    Beijing 100070

28. Hou Fushen, Director
    Hi-tech Development Department
    China Automotive Technology & Research Center
    Beijing 100070

APPENDIX B: LITHIUM-ION BATTERY TECHNOLOGY PRESENTATION

B.1 CURRENT STATUS: HEV BATTERIES

- Conventional lithium-ion batteries for HEVs appear about ready for commercialization.
- Major focus remains on cost reduction.
  - Low-temperature performance and abuse tolerance still remain issues.
    - Emerging technologies with nanostructure materials ($Li_4Ti_5O_{12}$ or $LiFePO_4$) appear to address these issues.
  - Batteries, even those incorporating "stable" materials, will require appropriate thermal management controls and electronic protection circuits to extend battery life and avoid thermal runaway.
  - Battery life projections of 10–15 years are based on limited data.

B.2 LITHIUM-ION BATTERY TECHNOLOGY

Advantages	Disadvantages
Highest Energy Storage	Relatively Expensive
Light Weight	Electronic Protection Circuitry
No Memory Effect	Thermal Runaway Concern
Good Cycle Life	3-h Charge
High Energy Efficiency	Not Tolerant of Overcharge
High Unit Cell Voltage	Not Tolerant of Overcharge or Over-Discharge

B.3 MICROSUN'S LITHIUM-ION BATTERY

High-Power Lithium-Ion Battery Design

- Cell Specifications:
  - Commercially Available Type HPPC 18650 (high power)
  - Cutoff Voltage: 3.0 to 4.2 V
  - Cell Rated Capacity: 1.6 A•h
  - Maximum Discharge: 20 A
  - Maximum Charge: 5 A (80% in < 15 min)
  - Cycle Life: >1,000 (80% charge)
- Module Specifications:
  - Module Design: 4 series × 5 parallel
  - Nominal Voltage: 14.4 V
  - Module Capacity: 8 A•h
  - Maximum Discharge: 50 A continuous, 100 A of 10-s pulses

- Charge Time: < 1 h (80%)
- Fully integrated cell balancing, safety circuit, and thermal management
- Dimensions: 4.30 in. × 5.30 in. × 2.75 in.

B.4 GOLD PEAK INDUSTRIES NORTH AMERICA

18650 at 2,650 mA·h and 42.5 g – 230 Wh/kg, 0.67 amp/cell (3 parallel)

Both High-Capacity Versions

Parameter	$LiSO_2$ Primary	Lithium-Ion
A	2 0	67
A•h	8.25	2.65
V	2.72	3.67
Cells	1.00	1.00
Wh	22.44	9.73
Kg	0.0850	0.0421
Wh	264	231

B.5 A 123 26650 LITHIUM-ION SPECIFICATIONS

Capacity	2.3 A·h
Energy	7.6 Wh (110 Wh/kg)
Nominal voltage	3.3 V
Cylindrical cell dimensions	25.9 mm dia, 65.4 mm H
Cell volume	34.45 cm3
Cell mass (without external tabs)	70 g
Impedance (1 kHz)	8 MΩ
Impedance (10 A, 10 s)	15 MΩ
Temperature range	−30°C to 60°C

B.6 KOKAM AMERICA

- Fast charge capability: max. 3°C
- High discharge capability: 10 ~ 20°C
- High power density: over 1,800 W/kg (high power cell)
- Longer cycle life: over 2,500 cycles @80% DOD
- Wide operating temperature: -30 ~ 60°C

- Environmental friendly: zero emissions
- Low energy consumption: lightweight
- Maintenance-free operation
- Low heat emission in high-discharging mode

Parameter	Power Cell	Energy Cell
Energy Density		
Wh/kg	120	200
Wh/I	240	400
Power Density		
W/kg	2,400	550
W/I	4,800	900

B.7 ELECTRO ENERGY, MOBILE PRODUCTS, INC., BI-POLAR LITHIUM-ION BATTERY TECHNOLOGY

- $LiCoO_2$ chemistry
- Cell capacity: 20 A•h
- Cell is capable of 5°C charge and discharge
- 8 stacks of cells, total number of cells is 112
- Total capacity: 160 A•h
- System energy: 8 kWh
- Cell weight: 100 lb
- Additional battery hardware weight (5–10 lb) will be required

B.8 SAFT HIGH-POWER LITHIUM-ION CELLS (VL20P)

- Nominal voltage: 3.6 V
- Average capacity: 20 A•h, 1°C after charge to 4.0 V/cell
- Minimum capacity: 18.5 A•h, 1°C after charge to 4.0 V/cell
- Specific energy: 187 Wh/kg
- Specific power: 1,811 W/kg
- Cell diameter: 41 mm
- Cell height: 145 mm
- Typical cell weight: 0.8 kg

B.9 HIGH-POWER TOYOTA 12-A·H CELL LITHIUM-ION BATTERY

- Voltage: 3.6 V
- Capacity: 12 A•h
- Specific power: 2,250 W/kg
- Specific energy: 74 Wh/kg
- Weight: 580 g
- Dimensions: 120 mm (L), 25 mm (W), 120 mm (H)

B.10 CURRENT STATUS: TECHNOLOGY CHARACTERISTICS

Conventional lithium-ion technology

- ❑ **Accurate SOC**
- ❑ **Excellent power density**
- ❑ **Good energy density**
- ❑ ***Well matched for charge-sustaining***

Emergent lithium ion technology (titanate anode or iron phosphate cathode)

- ❑ **SOC determination problematic**
- ❑ **Good power density**
- ❑ **Very good energy density**
- ❑ ***Well matched for PHEVs and potentially charge-sustaining HEVs***

NiMH

- ❑ **Difficult to ascertain the SOC accurately**
- ❑ **Good power density**
- ❑ **Abuse tolerant and proven technology**
- ❑ **Moderate energy density;** ***good for charge-sustaining HEVs***

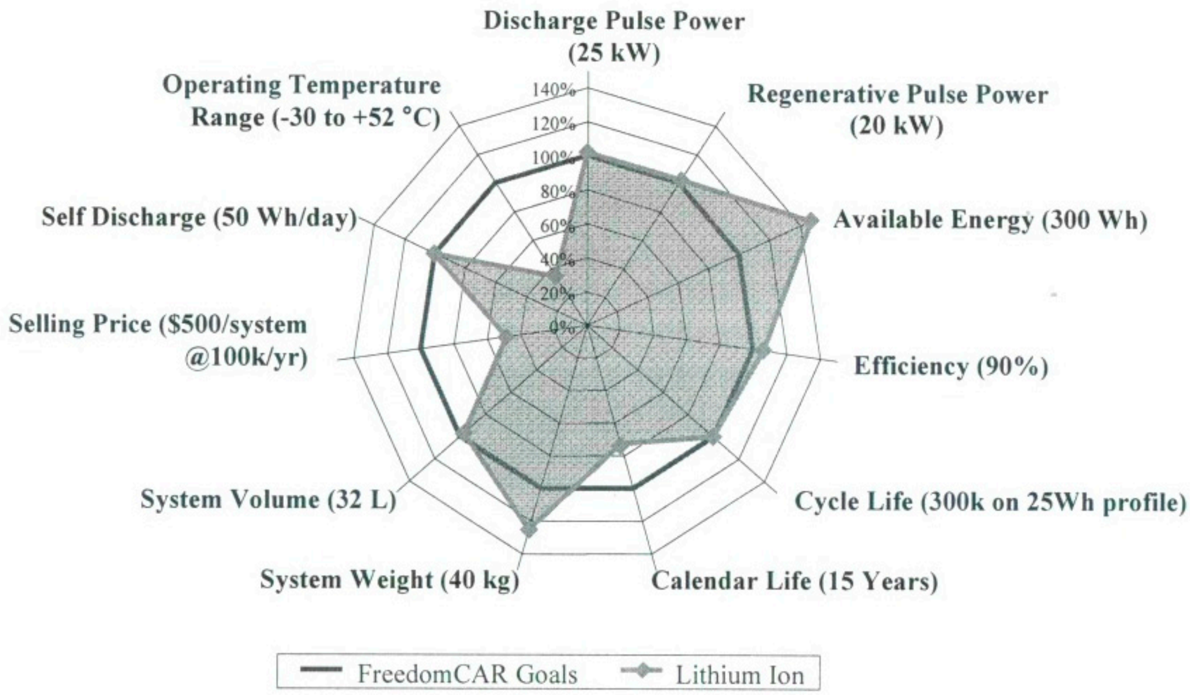
	HEV (Cell Energy, 10-s Power)	**EV** (Cell Energy, 30-s Power at 80% DOD)
Conventional lithium-ion technology	70 Wh/kg 2,500 W/kg	140 Wh/kg 500 W/kg
Emergent lithium ion technology	100 Wh/kg* 2,000 W/kg	
NiMH	50 Wh/kg 1,000 W/kg	65 Wh/kg 150 W/kg

* Projected

B.11 CHALLENGES FOR LITHIUM-ION LARGE BATTERY DEVELOPMENT

- Abuse tolerance – material and battery management
- Cost: cathode selection, volume, standardization, packaging, battery management
- Life: cathode selection, operating temperature, packaging
- Performance in extreme temperatures — all aspects of chemistry

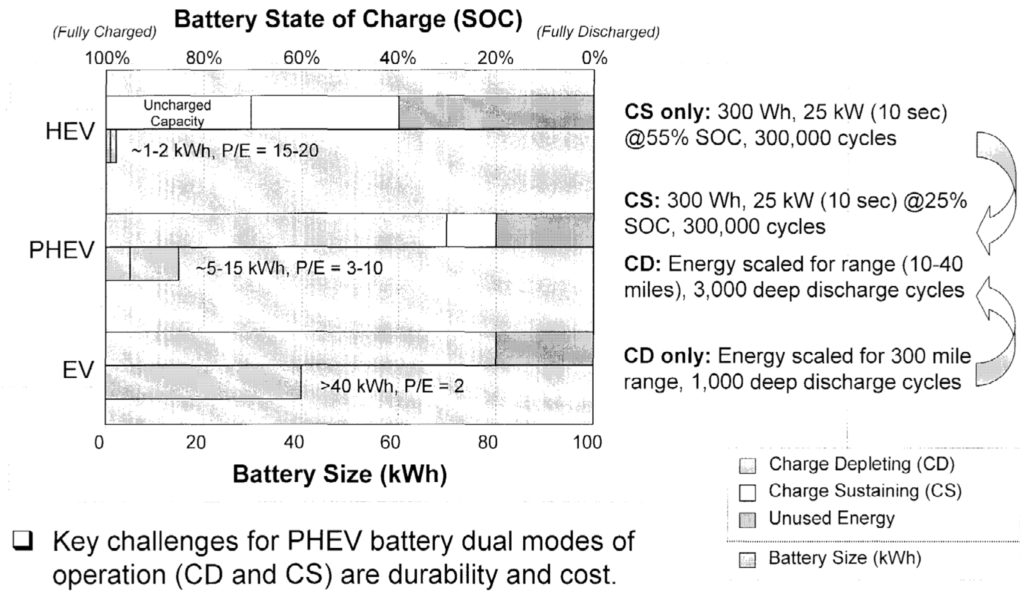
B.12 LITHIUM-ION BATTERY STATUS VS. GOALS FOR POWER-ASSIST HEV



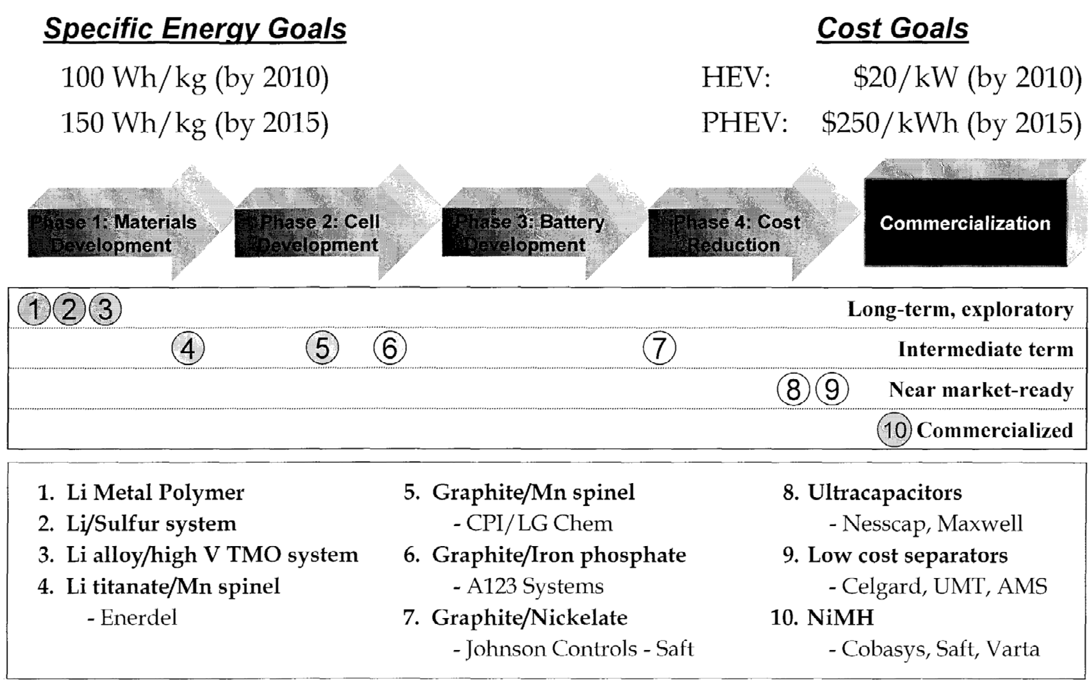
B.13 ELECTRIC AND HYBRID VEHICLE BATTERY REQUIREMENTS (MODULE BASIS)

Requirement Parameters	HEV	PHEV-20	PHEV-60
Vehicle ZEV Range (mi)	0	20	60
Battery Capacity (kWh)	<3	6	18
Cell Size (range corresponds to battery voltage 400V to 200V)	5–10	15–30	45–90
Specific Energy (Wh/kg)	>30	~50	~70
Specific Power (W/Kg)	~1000	~440	~390
Cycle Life			
Deep (80% DOD)	n.a.	>2,500	>1,500
Shallow (+/- 100 Wh)	200k	200k	200k

B.14 BATTERY REQUIREMENTS FOR TRANSPORTATION



B.15 ADVANCED BATTERY TECHNOLOGIES DEVELOPMENT STATUS



APPENDIX C: INTERVIEW QUESTIONS AND DISCUSSION TOPICS

The following questions were submitted to organizations developing lithium-ion batteries for discussions two weeks before meetings in the PRC.

1. Battery technology status: What is the level of development? Cell, module, or full pack?

2. Battery technology applications, power, energy, volume, and weight?

3. Testing methodology used? Charge/discharge limitations, cycle life, capacity, voltage, temperature operating range, and effect of aging?

4. Number of units produced per year, manufacturing facilities, and equipment used?

5. Any special feature(s) available on your current products?

6. Raw material availability domestically as well imported?

7. Where are your batteries sold? Domestically or exported? Are you working with any other companies overseas or domestically? How many batteries are produced for domestic use and for export purpose?

8. What is the cost of your battery domestically and overseas?

9. Is your battery cell, module, or pack available for testing and evaluation if we can work out a confidentiality agreement? Could we evaluate your technology at Argonne National Laboratory in the United States? When can you make the battery available for evaluation?

10. Are you conducting R&D at your facilities or with companies in China or overseas to improve your products or developing new products or technology? In general, what is the nature of your agreement? Is your company participating in joint venture or equity partnership?

11. Currently, are you working on batteries for electrical, hybrid, and/or plug-in hybrid vehicles?

12. Are you interested in pursuing battery development for electric, hybrid, and/or plug-in hybrid vehicles?

13. What is your company size? How many employees do you have? What are your sales per year (kW·h of capacity sold, or value sold in Yuan)?

14. Do you sell batteries directly as retail products? Do you sell batteries to other companies that convert them into packs with controllers? Is quality control causing you problems in selling batteries to some potential customers?

15. What are the incentives are offered by the Chinese Government to battery developers? Are these same incentives available to both domestic and/or international companies working with Chinese companies?

16. Do you have intellectual property, such as patents, joint venture agreements, or other rights to protect your products? How important are these for new product vs. improvement, venture vs. current manufacturer? Do you purchase battery technology and specialize only in production, or do you invest in battery R&D to develop your own products? If you do your own R&D, how much do you spend per year?

APPENDIX D: CHINESE LITHIUM-ION BATTERY DEVELOPMENT COMPANIES, CONTACTS, UNIVERSITIES, AND OTHER ORGANIZATIONS

LIST A

1. Beijing Waterwood Technologies Co., Ltd.
2. Topin Battery (China), Ltd.
3. Shenzhen Suppower Tech. Co., Ltd.
4. Shun Wo New Power Battery Technology, Ltd.
5. Sero Industrial & Commercial Co., Ltd.
6. Zhongyin (Ningbo) Battery Co., Ltd.
7. Shenzhen Win-top Electronic Tech. Co., Ltd.
8. Fujian Nanping Nanfu Battery Co., Ltd.
9. Hecell Hangzhou Battery Co., Ltd.
10. Shenzhen Mallerf Tech. Co., Ltd.
11. Hong Kong Eastar Industrial Co., Ltd.
12. Power Tech International Co., Ltd.
13. XELLEX Battery & Power Supply Tech. Co., Ltd.
14. Shenzhen Shunyi Industrial Co., Ltd.
15. GBP Battery Co., Ltd.
16. CLEScell International Battery Co., Ltd.
17. Wuhan Lixing (Torch) Power Sources Co., Ltd.
18. Sunhigh Battery(Primary Lithium) Co., Ltd.
19. Guangzhou Markyn Battery Co., Ltd.
20. Minamoto Battery Company
21. Golden Battery Technology Co., Ltd.
22. Wama Battery Co., Ltd.
23. Clescell International Battery Co., Ltd.
24. Able Battery Co., Ltd.
25. Guangzhou Great Power Battery Co., Ltd.
26. Narada Licom Power Tech. (Shanghai) Co., Ltd.
27. Megalink Company
28. Shenzhen Fekko Industrial Co., Ltd.
29. Totex International Limited
30. Hmc Power Technology, Ltd.
31. Tin Kam Company Limited
32. Shenzhen HJXY Li-Ion Battery Factory
33. Shenzhen Caixing Battery Factory
34. Hangzhou Lanbei Electric Bicycle Co., Ltd.
35. Jinhua Shiwei Vehicle Co., Ltd.
36. Hyper Power Co., Ltd.
37. Desay Power Technology Co., Ltd.
38. Yuntong Power Co., Ltd.
39. Huaye New-Technology Industry Co., Ltd.
40. Huangyuda

41. Huangyuda LTD Company
42. Zhongshan Mingji Battery Co., Ltd.
43. Hangzhou Huitong Industry Co., Ltd.

LIST B

1. Tianjin Lantian Double-Cycle Tech. Co., Ltd.
2. Tianjin Lishen Battery Joint-Stock Co., Ltd.
3. Beijing Green Power Tech Co., Ltd.
4. Beijing MGL
5. Shenzhen BAK Battery Co., Ltd.
6. Advanced Battery Technology, Inc., Ltd.
7. Hunan Corun Hitech Co., Ltd.
8. Degussa – ENAX (Anqui) Power Lion Co., Ltd.
9. Shenzhen Win – Top Electronic Tech. Co., Ltd.
10. Hecell Hangzhon Battery Co., Ltd.
11. Power Tech International Co., Ltd.
12. GBP Battery Co., Ltd.
13. CLEScell International Battery Co., Ltd.
14. Guangzhou Markyn Battery Co., Ltd.
15. Golden Battery Technology Co., Ltd.
16. Guangzhou Great Power Battery Co., Ltd.
17. Narada LiCom Power Tech (Shanghai) Co., Ltd.
18. Totex International, Ltd.
19. Hmc Power Technology, Ltd.
20. Shenzhen HJXY Li-Ion Battery Factory
21. Shenzhen Caixing Battery Factory
22. Hangzhou Lanbei Electric Bicycle Co., Ltd.
23. Jinhua Shiwei Vehicle Co., Ltd.
24. Hyper Power Co., Ltd.
25. Yuntong Power Co., Ltd.
26. Huangyuda
27. Wuhan Lixing (torch) Power Co., Ltd.

Institution and University Contacts:

1. Heliang Zhou, China Electro-Chemical Society, Beijing
2. Wang Tiqiang, Battery Technology Institute
3. Chen Quanshi and Dr. Jiang Fachao, Tsinghua University
4. Dr. Prof. Sun Fengchun, Beijing Institute of Technology
5. Prof. C.C. Chan, University of Hong Kong

LIST C

1. Tianjin Lantian Double-Cycle Tech. Co., Ltd.
2. Tianjin Lishen Battery Joint-Stock Co., Ltd.
3. Beijing Green Power Tech. Co., Ltd.
4. CITIC Guoan MGL
5. Suzhou Phylion Battery Co., Ltd.
6. General Research Institute for Nonferrous Metals (GRINM), Institute of Energy Materials and Technology Laboratory of Li-ion Battery

Institutions and Universities:

1. China Electrotechnical Society, Beijing
2. Tsinghua University
3. Tianjin Institute of Power Sources
4. Tongji University
5. Beijing Institute of Technology

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