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Factors Affecting U.S. Production Decisions: Why are There No Volume Lithium-Ion Battery Manufacturers in the United States?

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Abstract

The United States has been an incubator for new technologies for rechargeable batteries, while Asian companies have developed the manufacturing expertise and made the requisite capital investment to profit from these technologies. This investigation examines the circumstances attending lithium-ion (Li-ion) battery developments as a vehicle to seek a better understanding of the factors affecting decision-making of U.S. manufacturers, specifically addressing the question: "Why are there no volume Li-ion battery manufacturers in the United States?"

Abstract

The United States has been an incubator for new technologies for rechargeable batteries, while Asian companies have developed the manufacturing expertise and made the requisite capital investment to profit from these technologies. This investigation examines the circumstances attending lithium-ion (Li-ion) battery developments as a vehicle to seek a better understanding of the factors affecting decision-making of U.S. manufacturers, specifically addressing the question: "Why are there no volume Li-ion battery manufacturers in the United States?"

The conclusions are:

- The U.S. battery companies "opted out" of volume manufacturing of Li-ion batteries, primarily because of a low return on investment compared with their existing business, the significant time and investment required from conception to commercialization, and the time and expense required to establish a sales organization in Japan to access product design opportunities and take advantage of them.

- Labor costs were not a major issue impeding large-volume production of the cells in the United States. The cost of labor in the United States was essentially the same as for the Japanese manufacturers domestically. The Asian strategy of providing facilities and loans to establish manufacturing locally and create jobs was a more important factor.

- Structural differences of the Japanese electronic products industry compared with the U.S. counterpart create barriers for U.S. firms seeking to market rechargeable batteries or battery materials in Japan. In markets for rechargeable

batteries, customers are large, high technology-based electronics companies with their own battery manufacturing capability. Developing a product requires close contact with portable electronic device designers, which is more easily accomplished within the vertically integrated Asian companies than in the U.S. system where battery companies have little access to device designers.

- The tendency could be for technological development to follow manufacturing to East Asia, as a natural consequence of developing manufacturing expertise. Primary as well as rechargeable battery production will slowly shift to China, Korea, and Southeast Asia. U.S. manufacturers pursuing other budding energy technologies, such as fuel cells, will face similar issues.
- Opportunities still exist for U.S. companies to successfully enter niche markets, such as those with medical, military, or space applications. Mechanisms for cooperation between government-academia and industry need to be implemented to assure that advanced materials technologies have the resources and direction to succeed.

A Message About the Study

U.S. companies have made decisions not to become major commercial players in high-volume applications of rechargeable battery technology despite being at the forefront of its development. The situation is similar in other specific technology areas. ATP commissioned this study to understand what industry factors—global and domestic—affect the decisions of companies to make the investments needed for high-volume production in rechargeable batteries and certain other technology-based products. Learning more about these factors can assist ATP in evaluating the quality and credibility of proposals for ATP funding against the business-economic criteria and in assessing on-going commercialization planning.

To address this issue, we engaged Dr. Ralph Brodd, an international consultant with a long career in development and commercialization of battery technologies. For this study, Dr. Brodd conducted over 40 structured interviews with management individuals spanning major battery companies, materials and component suppliers, venture capital firms, start-up companies, original equipment manufacturers (OEMs), universities, and government and military officials.

Dr. Brodd has woven a story from this collection of interviews and his findings are documented in the study. As intended, the study presents the collective, peer judgment of international battery experts and is more anecdotal in nature than scientifically researched. The study confirms many preconceptions, and provides rich material for future study as ATP continues to seek a greater understanding of the factors important to the commercialization of new technologies and the complex pathways associated with delivering benefits in an international industry.

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About the Author

Ralph James Brodd is President of Broddarp of Nevada, Inc., a consulting firm specializing in technology assessment, strategic planning and battery technology, production, and marketing. He received a B.A. degree in chemistry from Augustana College, Rock Island, Illinois, and M.A. and Ph.D. degrees in physical chemistry from the University of Texas at Austin.

Dr. Brodd began his career at the National Bureau of Standards in Washington, D.C., studying electrode reactions and phenomena that occur in battery operation. He taught physical chemistry in the U.S. Department of Agriculture Graduate School and lectured in electrochemistry at Georgetown University and American University.

In the 1960s and 1970s, Dr. Brodd served in a variety of technical and management capacities with a number of battery companies. In 1961, Dr. Brodd joined the L.T.V. research Center of Ling Temco Vought, Inc., in Dallas, Texas, where he established a group in fuel cells and batteries. In 1963, he moved to the Battery Products Technology Center of Union Carbide Corporation, with technical management responsibilities for nickel-cadmium and lead acid rechargeable batteries, alkaline and carbon-zinc product lines, and exploratory R&D. He joined ESB (INCO Electroenergy, Inc.) in 1978, establishing a technology surveillance group, and moving to the position of Director of Technology with oversight and policy responsibility for R&D laboratories serving product areas ranging from primary and secondary batteries to uninterruptible power supplies and small electric motors. He was a member of the INCO Long Range Technology Committee and the technical advisory panel for North America Capital Venture Fund.

In 1982, Dr. Brodd established Broddarp, Inc., a consulting firm specializing in battery technology, strategic planning, and technology planning. A consultancy with Amoco led to his moving to Amoco Research Center as project manager of a rechargeable lithium sulfur dioxide battery project. He subsequently moved to Gould, Inc., to establish their Lithium Powerdex Battery Venture and then to Valence Technology, a venture group developing a solid polymer electrolyte battery system for rechargeable batteries for portable consumer devices. He served as staff consultant/marketing director and then Vice President, Marketing.

Dr. Brodd was elected President of The Electrochemical Society in 1981 and Honorary Member in 1987. He was elected National Secretary of the International Society of Electrochemistry, 1977-1982, and Vice President, 1981-1983. He is past chairman of the Board of Directors of the International Battery Materials Association. Dr. Brodd was President of the Pi chapter of Phi Lambda Upsilon.

Dr. Brodd has served on numerous technical advisory and review committees for the National Research Council, International Electrotechnic Commission, DOE, NASA, and NIH government laboratories and technical programs, most recently as a member of the 1999 and 2004 Review Committee for the Environmental Energy Technologies Division of Lawrence Berkeley National Laboratory. Dr. Brodd has over 100 publications and patents.

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Executive Summary

The United States has continued to lead in developing new technologies and is the major source for new concepts in battery, fuel cell, and other budding technologies supporting the nation's energy and portable communications future. Asian and European companies, however, are developing the manufacturing expertise to commercialize many of these technologies.

In the area of advanced rechargeable batteries, and other areas as well, the Advanced Technology Program (ATP) has funded projects that were technically successful, but where the outlook for U.S. companies' becoming major commercial players in high-volume applications is not promising now. U.S. companies have opted out of many markets. ATP seeks to better understand the factors affecting commercialization of technology as a means of:

- providing guidance for the proposal evaluation and selection process,
- aiding in monitoring the business opportunities progress of technologies currently under development, and
- contributing to the development of U.S. science and technology policy.

This study uses the case of lithium-ion (Li-ion) batteries to seek a better understanding of industry factors that affect the introduction of new rechargeable batteries and similar types of technologies into the marketplace.

Background

Li-ion batteries power the devices of the digital revolution—including telephones, music players, digital cameras, and notebook computers. Today's typical mobile phone owes its size and weight reductions largely to the advent of the Li-ion rechargeable battery.

Over the past 10 years, the market for Li-ion systems has grown from their commercial introduction with minimal production in 1992 to over $3 billion in 2003. This technology sparked the expansion of cellular telephones and notebook computer applications. Production of Li-ion cells originally centered in Japan, but new manufacturers with significant production capability have now appeared in China and Korea.

U.S. researchers were once on the leading edge of key technical developments enabling the Li-ion battery systems in use today. The National Electronics Manufacturing Initiative (NEMI) roadmap studies recognized advanced rechargeable batteries as a critical component in the growth of portable electronic devices. The U.S. battery industry was aware of the importance of this emerging technology, but did not try to compete with stronger players overseas. In spite of the rapid growth of this important market segment, the United States has no large volume producers of this technology. There are several reasons for this.

Why are there no volume Li-ion manufacturers in the United States?

- The U.S. battery companies "opted out" of volume manufacturing of Li-ion batteries, primarily because of a low return on investment compared with their existing business. Duracell and Energizer both started, but later abandoned, programs for production of rechargeable Li-ion batteries. They decided not to compete with companies based in East Asia, which can tolerate lower profit margins due to structural advantages in their home countries. A secondary consideration was the time and expense required to establish a sales organization in Japan to access product design opportunities.

- The cost of labor is not as significant as is commonly believed. Production of Li-ion batteries consists of both unit-cell production (which can be automated to a high degree) and battery pack assembly (which is most cost effective as a manual process). Automated unit cell production offsets the advantage of locating production in East Asia. However, establishing an automated production facility requires a minimum investment of about $120 million.

- Sales and marketing of rechargeable batteries differ significantly from the marketing of primary batteries, where U.S. firms have a strong marketing and distribution network. In rechargeable batteries, customers are large, high technology-based electronics companies. Developing a product requires close contact with portable electronic device designers who choose the battery to power the device. Most producers of portable electronic devices are located in Japan in companies that are both producers and user/customers of rechargeable batteries.

- American companies are better able to compete in small-scale, high-quality, high-profit-margin niche rechargeable battery markets, such as those with medical, military, or space applications, rather than in large-scale production.

- American manufacturers will continue to be competitive in the market for primary batteries. Their strengths lie in their distribution networks and in marketing coupled with low-cost, highly-automated production.

- No simple explanation accounts for the lack of a large-scale producer of Li-ion batteries in the United States. The subsequent discussion, however, provides reasons for the dominance of companies from East Asia in this arena.

Factors Affecting U.S. Production Decision

Several East Asian countries, including China, South Korea, Taiwan, and Malaysia, as well as Japan, have internal structural advantages for domestic companies over what U.S. companies experience at home; these encourage commercialization of new technology. Some European countries have also developed such advantages, but Japan is the archetypical example. These structural advantages include:

- **Lower Cost of Capital—**More significant than lower labor costs, many countries have a better investment climate than has the United States. The cost of capital is lower in Japan because of its greater availability (owing to high savings rates). Because unit cell battery production is highly automated, labor costs are a relatively minor component of cell production costs.
- **Reliance on Loans rather than Stock Sales for Operating Capital—**American companies tend to focus on short-term profits and stock prices, while Asian companies seek market share. American managers are held accountable and valued based on company profitability and stock price. Asian managers are more likely to defer near-term profits in favor of investing for long-term success as reflected in market share. Japanese companies rely more on bank loans to fund R&D and new production facilities.
- **Government Coordination of R&D—**The Japanese government works with industry to identify new technologies that are ripe for near-term economic exploitation. Government then encourages companies that will eventually be competing with each other to share information and cooperate during the early stages of development. This contrasts with the U.S. pattern of business-government relations, which can sometimes be adversarial.

American companies sometimes move production to East Asia to take advantage of government incentives or lower labor costs. This inevitably results in an eventual transfer of technology to the host countries—product as well as production technology. Batteries are only one example. Two others considered in this study were fuel cells and electronic chips and components. Fuel cells have a short window of opportunity to begin manufacture in the United States. Manufacture of electronic components, such as displays, will likely follow the course of IC chips and Li-ion batteries to Asia.

These factors should be kept in mind when ATP evaluates the likelihood that new battery and related technologies will be commercialized in the United States. These are the factors that have demonstrated the most leverage in U.S.-firm decision-making. Although Japan has lately been suffering economic malaise, it is a misperception that the advantages that Japan enjoyed though the 1980s no longer apply.

Conclusion

The United States still leads in developing new technologies and is the major source for new concepts in battery, fuel cell, and display technologies. The United States is an incubator for new technologies relating to the electronics industry, while the Asian and European companies develop the manufacturing expertise. There could be a tendency in the future for technological development to follow manufacturing in moving to East Asia as a natural consequence of Asian companies' development of manufacturing expertise.

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I. Introduction

Study Objectives

The Advanced Technology Program (ATP) is a government-industry partnership that cost shares with private industry the funding of high risk R&D with broad commercial and societal benefits. These projects would not likely be undertaken otherwise because the risks are too high or the benefits would not accrue to private investors. Through a competitive selection process, ATP chooses projects by applying evaluation criteria, (1) scientific and technological merit (50 percent), and (2) potential for broad-based economic benefits (50 percent). ATP source evaluation boards are thus charged with assessing the potential economic benefits to the United States of projects under consideration for funding as well as the technical merit.

It is anticipated that the major benefits accrue through creation of new products and processes embodying ATP-funded technologies and their successful commercialization. Of primary interest to this publicly-funded program are the benefits to industries and individual consumers and users of these technologies, rather than to the individual companies that are funded directly. U.S. technology users benefit from goods produced off shore as well as those produced domestically. Nevertheless, offshore production will change the flow of benefits from a U.S. investment in R&D and may reduce the benefits to the United States. The ATP seeks to better understand the factors affecting commercialization of technology in the United States by U.S. companies as a means of:

- Providing guidance to the proposal evaluation and selection process;

- Aiding in monitoring the business opportunities progress of technologies currently under development; and
- Contributing to the development of U.S. science and technology policy.

This study uses the case of Lithium-ion (Li-ion) batteries to investigate factors affecting decisions of U.S. companies to set up production for new battery technologies. U.S. scientists have spearheaded R&D in areas where the dominant manufacturers are now abroad. Lithium-ion batteries, which power the devices of the digital revolution—including telephones, music players, digital cameras, and notebooks—are a case in point. Today's typical mobile phone owes its size and weight reductions largely to the advent of the Li-ion rechargeable battery. Yet despite many years of electro-chemical research in the United States, Japanese companies took commercial advantage of the innovation and transformed it into a useful product, while U.S. companies did not.

With the assumption that future battery and other technologies may be expected to experience commercialization pathways similar to the Li-ion case, this study seeks answers to the following questions:

a. Why are there no large volume producers of rechargeable Li-ion batteries in the United States?

b. What are the factors affecting the introduction of new technology into the marketplace?

c. What are the implications of the findings for other developing technologies, for example, fuel cells, displays, and other electronic components?

Methodology

We conducted interviews with more than 40 individuals in the lithium-ion battery industry worldwide to establish the relative impact of various factors on investment and manufacturing decisions of Li-ion battery manufacturers and to identify the principal factors that have limited the development of large volume production of rechargeable Li-ion batteries for the portable electronic market in the United States.

The interviewees included individuals in industry, government, and academia. Individuals interviewed from industry included representatives from materials suppliers and electronics firms that use Li-ion batteries in their devices as well as representatives from battery manufacturers serving in technology, management, and marketing positions. Appendix 2 lists the company affiliations of the individuals interviewed.

Each interviewee received a list of questions in advance that served as a guide to the interview process. Appendix 1 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 free-flowing manner, allowing the experts to focus on what they considered to be most important factors influencing production decisions of Li-ion manufacturers.

Their responses assisted us in identifying and analyzing structural differences that appeared to account for disparities in Li-ion industry outcomes in the United States and Asian countries.

II. Rationale for Li-ion Case

U.S. scientists have long spearheaded research and development in various battery chemistries, and U.S. battery manufacturers have maintained dominant positions in the primary battery market. North American researchers provided many of the critical technology breakthroughs needed to establish Li-ion battery feasibility. Yet today, the dominant secondary (rechargeable) battery manufacturers are abroad, and U.S. manufacturers appear only in niche markets and boutique applications.

U.S. Activity in Li-ion R&D

A National Electronics Manufacturing Initiative (NEMI) study pointed out the advantages of the Li-ion technology in the mid 1990s. This study designated Li-ion as a critical technology in the development of portable electronic devices. In 1998, the NEMI, which is made up of the major U.S. electronic manufactures and suppliers, stated:

> The rechargeable battery technology has long been a critical bottleneck in development of improved portable electronic products for communications and information sectors. While the United States is a leader in advanced battery research concepts, it is vertically integrated foreign competitors that have come in the 1990s to dominate the two new rechargeable battery technologies: Ni-MH (employed in mobile computing since 1993) and Li-ion/liquid electrolyte batteries. In 1998, the National Electronics Manufacturing

Initiative (NEMI) laid out a technical roadmap (1) with targets that, if achieved, would result in performance significantly improved over today's batteries:

Gravimetric energy density: 250 Wh/kg
Volumetric energy density: 475 Wh/l
Cycle life: 2000
Cost: $1/Wh.[1]

Today, typical cells have exceeded the Wh/l goal (500 Wh/l) and the cost target ($0.30/Wh) and are approaching the 250 Wh/kg goal. In addition, research results on new materials offer the possibility of doubling the energy goals. For the first time, a rechargeable system has greater energy storage capability than the standard alkaline cell. This will have strong implications for the future of primary batteries, as the cellular telephone and notebook computer have taught the discipline of recharging the battery in a device on a regular basis.

Over the past few years, the battery industry has seen a major shift in the technology for portable power applications. Li-ion batteries, which did not come into existence until the early 1990s, have become a standard for high-energy rechargeable battery technology and have captured the bulk of the portable device market. They have four times the energy and twice the power capacity of nickel cadmium (Ni-Cd) batteries, do not experience memory effect (where partial discharge before recharge reduces length of next cycle), and have a 50 percent longer life cycle. Compared with nickel-metal hydride (Ni-MH) batteries, they have twice the energy, and they can be produced at a much lower cost. They are environmentally friendly, and their high average voltage of 3.6V make them ideal for powering a new generation of low-power 3-G electronics. These factors all have contributed to this relatively new battery technology’s complete domination of the notebook computer and cellular telephone markets.

1. NEMI Technology Roadmap, December 1996, p. 117.

> Without the Li-ion battery, introduced a decade ago, portable electronic products—from mobile phones and video cameras to notebooks and palmtops—would have remained brick-like objects best left on the desk or at home. But the innovation would have floundered had electro-chemist researchers in the U.S. and England not teamed up with a Japanese firm.
>
> The development of the lithium-ion battery is an object lesson in how pure and applied research driven by commercial interests, can generate incremental improvements in a technology that are necessary for transforming it into a useful product. In this case, intercalation compounds were an offshoot of pure research into superconductivity. They were then picked up by Dr. Goodenough and other researchers working on battery technology; and the final pieces of the puzzle were supplied by Asahi Chemical and Sony. (Dr. Goodenough, who did his original research at Oxford [and later work at University of Texas-Austin], says battery firms in the West rejected his approaches).[2]

The United States has been, and is, a very fertile ground for developing new technologies for application in the advanced battery arena. North American researchers provided many of the critical technology breakthroughs required to establish Li-ion polymer battery feasibility.

Prominent in the historical narrative, Dr. John Goodenough invented lithium cobalt oxide cathode materials while at Oxford University. His technology was used in the first commercial Li-ion battery, launched by SONY in 1991. More recently, at the University of Texas, Austin, Dr. Goodenough patented a new class of iron phosphate materials with potential to replace the more costly cobalt materials. In 2000, he

2. "Hooked on lithium," Economist Science Technology Quarterly, June 20, 2002.

received the prestigious Japan Prize for his discoveries of the materials critical to the development of lightweight rechargeable batteries.

Other U.S. scientists working in this area abound. The work of Dr. Philip Ross at Lawrence Berkeley Laboratories using ab initio calculations gives great insight in identifying electrolyte components and additives to improve Li-ion performance. Dr. Stan Ovshinsky's team at Energy Conversion Devices has provided many of the concepts driving Ni-MH battery technology.

U.S. Manufacturing of Li-ion Batteries

There are many other examples of work by U.S. researchers that directly affected advanced battery systems. However, the United States has no large volume manufacturers, with only a few firms producing small volumes for specialty and military applications. U.S. companies, although global leaders in primary battery production and technology, were unable to take advantage of this early technological success. Their Southeast Asian counterparts have captured a dominant position in Li-ion battery manufacturing. Huge investments have been made in Japan, Taiwan, Korea, China, and other countries in Southeast Asia by both companies and government friendly policies for investment in competitive efforts to capture global market share for rechargeable batteries for telecommunications, wireless, and computer products.

The two major U.S. battery manufacturers, Duracell and Eveready (now Energizer Holdings), began R&D efforts in Li-ion technologies around 1992, with the intent of ultimately manufacturing Li-ion batteries.

According to several senior staff interviewees, Duracell and Energizer both initiated programs for production of Li-ion batteries. In 1997, Energizer built a manufacturing facility in Gainesville, Florida outfitted with state-of-the-art equipment to produce Li-ion batteries, with production slated to start in 1999-2000. They licensed a Goodenough patent from Sony and built on their own advantaged IP positions in several areas. They had several years of experience with manufacturing Nickel Cadmium (Ni-Cd) and Ni-MH cells in Gainesville for several cellular phone and notebook computer companies. They prepared to establish a sales and marketing group in Japan to have access to the market, knowing it would take 5 years to be accepted. When the Gainesville Li-ion plant was in the "prove-in" stage, nearly ready for production, the world market price for Li-ion cells abruptly declined. The company reassessed the profitability of their investment and found it was marginal at the low cell prices. They could buy cells from Japan at a lower price than their manufacturing costs. The decision to exit Li-ion manufacture followed swiftly. The news of the low return to manufacture of Li-ion cells spread to Duracell, and they stopped their project. (Energizer sold its Gainesville facility to Moltech Corporation in 1999 after it sat idle for two years. In 2002, Moltech sold the plant to U.S. Lithium Energetics, which is seeking capital to enter production.)

Small U.S. companies and start-ups have continued to pursue innovative R&D with early-stage R&D funding from Defense Advanced Research Projects Agency (DARPA), the Advanced Technology Program, the Small Business Innovation Research program, and other federal programs. Novel Li-ion chemistries have helped carry them forward toward commercial targets. These new ventures have been most successful in niche markets (military and medical applications). New ventures have had little success in the development of significant, sizable new markets for their products. Without economies of scale, their costs of production remain high. Venture capital-funded companies tend to look off-shore for their production to mitigate the high cost of automated production equipment. Some U.S. companies with larger-scale applications have also moved offshore.

Several ATP-funded companies illustrate a spectrum of successes and failures. While large battery companies have been reluctant to enter medical markets due to liability concerns, Quallion and its joint venture partner Valtronic are developing Li-ion technology to power implantable medical devices. The company is on a steep growth path.

U.S.-made Li-ion battery powers tiny implants that aid neurological disorders

Early batteries for medical microelectronic devices were large, had short lives, and were not rechargeable. As a result, only a few implantable devices, such as cardiac pacemakers, have come into patient use. With assistance from its Advanced Technology Program award in November 2000, Quallion and joint venture partner Valtronic are developing a Li-ion technology for a battery to power implantable medical devices. The goal is to be able to recharge the battery from outside the body with no physical connections.

Alfred Mann, chairman and co-founder of Advanced Bionics Corporation, started Quallion LLC after being unable to find a company to make tiny Li-ion batteries to power the injectable neuromuscular stimulator he was developing in the late 1990s. With a size no bigger than a grain of rice, the tiny Li-ion battery had to have a 10 year life, be rechargeable thousands of times over, be hermetically sealed for safety reasons, and have the capability to remain dormant for long periods of time without losing its power.

The success of the Quallion battery is due to an advanced Li-ion chemistry that provides a useful lifetime significantly greater than lithium batteries that are commercially available. The ever smaller implantables will need ever smaller batteries to power them. Potential solutions are coming from the research labs and startups like Quallion, and not the large battery companies. The large companies have been reluctant to enter this market because of the technical risks in developing an implantable that will function properly in the body and the legal ramifications following a life-threatening battery failure.

Potential uses include treatment of chronic pain, epilepsy, sleep apnea, and restoration of limb control for stroke victims. Feasibility trials are currently under way on patients suffering from urinary tract incontinence. The cost of the battery by itself is initially running around $400, according to Quallion's president Werner Hafelfinger. It is recharged from outside the body through a special pad attached to a belt or placed on a seat or bed.

Starting with only 2 scientists in 1998, the Sylmar, California, company more than doubled in size every 6 months, and today Quallion employs over 100 people.

Sources: Argonne News Release, "Battery powers tiny implants that aid neurological disorders (September 19, 2003) on Argonne National Laboratories website www.anl.gov/OPA/news03/news030919.htm; and *Small times*, "When lives are at stake, the batteries better work" (June 26, 2003) on their website <www.smalltimes.com>.

PolyStor, a spin-out of the Lawrence Livermore National Laboratory, developed state-of-the-art Li-ion technology, but the company failed following unsuccessful efforts to market its product for cell phone applications in the face of severe price competition between Japanese and Chinese battery companies seeking market share.

Small U.S. company takes foot steps in Li-ion battery production

Polystor Corporation, a privately held company based in Livermore, California, developed and manufactured rechargeable Li-ion and Li-ion polymer batteries in small volumes for mobile devices and portable electronic products. Polystor developed a nickel cobalt oxide cathode that delivered the highest capacity and energy density in the industry at one point.

The firm was founded in 1993 to bring to the market technology that was developed by its founders while at the Lawrence Livermore National Laboratory. The firm pursued development of Li-ion technologies for the Strategic Defense Initiative program. In the 1990s, with assistance in R&D funding from a TRP grant, several SBIR grants, and a grant from the U.S. Advanced Battery Consortium, the company sought to spin the technology out for commercial use.

PolyStor's Li-ion cell was tested by Motorola and other major manufacturers and reached production by 1996. PolyStor made the cell components in the U.S. and shipped them to Korea for assembly.

In 2000, PolyStor won an award from the Advanced Technology Program to help develop a safe, ultrahigh capacity next-generation rechargeable battery based on Li-ion polymer gel technology.

After suffering a sharp decline in demand for its products in 2001, tied to a global decline in the demand for cell phones, PolyStor ceased operations in 2002.

Source: Steve Peng. "Mold to Fit Battery." *Edgereview* at <www.edgereview.com>.

PolyPlus, with joint venture partners Eveready (now Energizer Holdings) and Sheldahl, received ATP funding to develop lithium-sulfur battery technology spun out of Lawrence Livermore National Laboratory. The partnership among small and large companies failed to see the anticipated commercialization pathways when the project encountered technical difficulties and Energizer exited the market for rechargeable batteries.

Small U.S. company continues to obtain financial assistance for lithium-sulfur rechargeable battery R&D

With its ATP award in 1999, PolyPlus Battery Company (Berkeley, CA), in a JV with joint-venture partners Sheldahl, Inc. (Northfield, MN) and Eveready Battery Company, Inc. (now Energizer Holdings, Westlake, OH), aimed to develop and test rechargeable, long-life lithium-sulfur batteries that offered increased energy density, reduced size and manufacturing cost, and enhanced safety as power sources for mobile technologies such as notebook computers and cell phones.

PolyPlus was to develop processes for depositing the layer of glass and specifying the battery chemistry. Sheldahl's role was to develop the protected lithium metal electrode (with assistance from subcontractor Sidrabe), and Eveready was to develop the glass electrolyte and cathode and construct test batteries.

Eveready Battery Company, Inc., incorporated in 1986 by Ralston Purina Company to acquire the long established battery products business of Union Carbide Corporation, became a leading manufacturer of primary batteries and battery-powered flashlights. In 2000, Ralston-Purina spun off Eveready as Energizer Holdings, Inc., an independent company, and sold

Eveready's OEM rechargeable battery business to Moltech Corporation for manufacture and assembly of battery packs for a variety of battery-powered devices and tools.

The ATP–funded project encountered technical difficulties in the second and third years of the project, particularly in protected anode development. By the end of the ATP project, Eveready/Energizer announced it did not plan to pursue the technology. By 2000, Eveready/Energizer had essentially exited the market segment where lithium-sulfur technology would best fit. Energizer currently estimates it has a 30 percent share of the U.S. alkaline battery market. It has not announced any revolutionary changes in its battery technology.

PolyPlus continues to pursue leading-edge lithium battery research and development and to conduct the independent research upon which the company was founded, both on contract research and in joint development projects with battery manufacturers and others, with financial support from individual angel investors, venture capital, and large companies Energizer and Samsung.

In 2002, Moltech Corporation sold the Li-ion facility acquired from Energizer to U.S. Lithium Energetics LLC. Moltech continues as a small but fully integrated provider of rechargeable battery solutions for many applications. Now called Sion Power, the company is concentrating on developing and commercializing its own thin-film, lithium-sulfur rechargeable battery technology.

Source: ATP Project Brief, project number 99-01-6015; Abstract 53, IMB 12 Meeting, Electrochemical Society; Hoover's Online.

PowerStor, a subsidiary of PolyStor, received ATP funding to develop aerogel capacitor technology licensed from Lawrence Livermore National Laboratory. More successful than its parent company, PowerStor illustrates the movement toward offshore production for larger-scale applications.

Offshore manufacturing enables small company to manufacture without capital investment in production facilities

PowerStor, a subsidiary of PolyStor, licensed aerogel capacitor technology from Lawrence Livermore National Laboratory. PowerStor overcame financial barriers to constructing production facilities by manufacturing its aerogel ultracapacitor products by hand in Malaysia. This approach required minimal capital and quickly resulted in product sales. More than 10 million of these devices have been sold in Asia, Europe, and the United States, with new applications emerging monthly.

Microsoft uses the capacitor to power the clock in its new gaming console system. Several aviation equipment manufacturers install the device in aircraft displays to maintain continuous voltage when switching from one electrical bus to another. Other applications include low-tech toys, valve actuators, and insulin pumps.

Cooper Electronic Technologies acquired PowerStor when the parent company, PolyStor, folded.

Source: Missile Defense Agency 2003 Technology Applications Report: Electrical, Electronic, and Magnetic Devices.

Other examples abound.

- Valence Technology is a U.S.-owned, Austin, TX-based producer of Li-ion polymer batteries. Following R&D in the United States, Valence set up battery manufacturing operations in Northern Ireland because of financial incentives by Invest Northern Ireland. Its production is small in scale compared to Sanyo or Sony. It has mounted an extensive campaign to sell its lithium vanadium phosphate cathode batteries for notebook and cellular phones. The Valence battery is available through their web site and distributors, but sales have been disappointing. After two years in the market, sales were less than $5 million per year. Valence announced in 2003 that the company would move its production from Northern Ireland to China to take advantage of lower production costs there than in Northern Ireland.

Ultralife and Eagle Picher Industries were joint-venture recipients of ATP funding to develop polymer Li-ion batteries for portable electronics devices used in commercial space applications. Eagle-Picher has developed Li-ion production capability in Canada targeting the U.S. military market, as did Yardney. Ultralife is now largely concentrating on the niche markets in smoke detectors and military radio applications using its lithium manganese primary cell platform.

- With a twist in this off-shore strategy, Long Island-based Brentronics buys cells from Japan and China for use in military packs. After assembly into battery-packs in the United States, they are marked “Made in USA.”

This study seeks to identify and analyze the reasons for the specific decisions by the two largest U.S. battery companies to cancel plans for Li-ion production. At the same time, the study establishes the business environment facing smaller companies and examines key factors affecting their success or failure.

III. The Innovation Process for Battery Technologies

Understanding the production decision requires first understanding the innovation process. The introduction of a new battery technology is a complex, expensive, and time-consuming process. As with all technology developments, it starts with an idea that has potential for a significant business opportunity. This might be an improvement on a present product, such as a new material, or a more efficient manufacturing process. It could be an entirely new product or material, which is less expensive or higher in performance than existing products. It could also be a new process with potential to lower product costs and increase sales.

Figure 1 depicts the five stages in the product innovation process: 1) concept generation and validation, 2) research, 3) applied research, 4) development, and 5) advanced development or pilot plant operations. This process holds for any technology development effort, not just for batteries. This figure provides a brief description of each category and the type of activity that occurs during that phase. Figure 1 also includes an estimate of the timing, staffing requirements, materials usage, and the relative cost of each stage. For example, the cost of the Advanced Development stage in approximately 50 times the cost of the Concept Validation stage.

It is difficult to assign an absolute time span for each segment. Some concepts are abandoned when they fail to yield their initial promise, while some can be accelerated when experimental results confirm such promise. One constant is that

Figure 1. Schematic of the Overall Battery R&D Process from Conception to Production

Concept Generation → **Production**

	Concept Validation	Research	Applied Research	Development	Advanced Development
	An idea in a creative mind Limited exploratory laboratory experiments Establish repeatability of performance Is there a market?	Scale-up experiments Characterize fundamental properties of concept, chem. composition, structure, etc. Evaluate size of commercial opportunity	Lab/prototype cells Initial map of performance, rate, cycling, temperature, etc. Scale-up of material preparation Preliminary market scope	Confirm research results Establish initial product format Develop unit assembly operations Make, test, and characterize 5 to 10 cell lots of 100 cells each Construct business plan	Design initial cell product Design and construct unit operations Scale-up prototype cell fabrication Run 3 to 5 sizable pilot line-factory trials Finalize business plan Market development
Timing	One to three years	One to three years	Three to four years	Three to five years	Two to four years
Staffing	One	Two to four	Four to ten	Eight to sixteen	Twelve to thirty
Materials Batch	Grams	10 to 50 g	100 g to 1 kg	1 kg to 10 kg	10 kg to 100 kg
Rel. Cost Index	1	2	5	20	50

each new concept has its own unique time to fruition. Concepts that show promise and yield early confirmation may be accelerated in order to reduce time to market. The chart reflects that, for the battery industry historically, the maximum time from conception to advanced development and actual product introduction totals 19 years. This corresponds closely to the actual time line for introduction of the alkaline cell, which is today's standard for performance of primary cells. The alkaline cell discovery occurred after the end of World War II, in the late 1940s. It was based on substituting manganese dioxide for mercury oxide in the Ruben cell. An initial product introduction by Rayovac failed in the mid 1950s. Eveready and Duracell introduced the product as we know it today between 1968 and 1970.

The chart also suggests that the process can be completed in as quickly as 10 years, as happened with the Li-ion technology. Work started in Japan in the early 1980s at Asahi Chemical Company, with the substitution of a carbon intercalation anode (based on the results of Basu, Besenhard, and Yazami) for the lithium metal anode coupled with lithium cobalt oxide for vanadium oxide (based on the Goodenough results for lithium intercalation into transition metal oxides). Sony announced the product in 1991 and made commercial cells available in late 1992. Thus, the Japanese companies moved extremely rapidly through the development and commercialization processes for Li-ion cells, as they have for many electronics innovations in the past decade. The U.S. companies anticipated the longer time frame. However, the new technology was quickly adopted for cellular telephones and notebook computers because of its smaller volume and significantly lighter weight than Ni-Cd and Ni-MH.

New product introduction in the battery business is a risky activity. Line extensions and new sizes in a product line generally take one to two years. The processes are slow and quite expensive. An estimate of the total cost of developing a new battery technology, from concept to production, is about $100 million. This includes a small pilot operation, but does not include the cost of the production facility.

The ability to fabricate prototype cells that closely approximate those that will be used during product introduction is essential throughout the R&D process. It takes considerable time and testing to determine the nature of the interaction between the various components of the cell. The stability of a given design might not be fully understood until years after its introduction.

Essential to commercial success is early input from the marketing group to determine features of the initial product line, such as the main application(s), size, rate of discharge, and ampere-hour capacity. Technology and marketing groups generally make the decisions to pursue new technologies. Companies conduct regular reviews of their technical programs with sales and marketing groups at least once a year and sometimes quarterly. The production operations get involved during the advanced development stage of product introduction in order to assist in the transition to market introduction.

Although many R&D projects are undertaken, few are selected for commercialization. The commercialization decision occurs when a project transitions to applied research. George Heilmeier, Chairman Emeritus, Telcordia (formerly Bellcore) provided us with the paradigm in Table 1.

This catechism is a succinct but generally representative view of how one might rate the value of a technology project and its chances of success. Several vice presidents of sales and technology said that an R&D project must have definite potential to contribute significant sales and profits to be carried forward.

Table 1. "Catechism" for Screening "Winners"

1. What are you trying to do? (No jargon, please.)
2. How is it done today? What are the limitations of current practice?
3. What is new in your approach, and why do you think it can succeed?
4. Assuming success, what difference does it make to us and to our customers?
5. What are the risks and what can we do about them?
6. How long will it take? How much will it cost? When are the mid-term and final exams?

Source: George Heilmeier, Chairman Emeritus, Telcordia.

IV. Structural Factors Affecting Production Decisions

Our interviews revealed strongly contrasting business environments in the United States compared with Asian countries with burgeoning activity in rechargeable batteries. The different market structures and other characteristics underlying these varied environments favor manufacturing of rechargeable batteries in these Asian countries, typified by Japan, which manufactures 80% of Li-ion batteries today.

Table 2 summarizes some differences in the business environments in the United States and Japan that emerged during interview discussions. In general, Japanese firms have enjoyed more supportive government policies and financial conditions. Although Japan has lately been suffering its own economic malaise, it is a misperception that the advantages that Japan enjoyed though the 1980s have disappeared. And other East Asian companies seem to be following Japan's example.

This section explores the different structural factors in the contrasting national business environments in greater detail in order to seek answers to why U.S. firms failed to successfully engage in Li-ion battery manufacturing despite their dominance in primary batteries.

Table 2. Characteristics of Business Environment in the U.S. and Japan

United States	Japan
Goal is immediate profits and maximum personal income	Goal is to gain market share
Short-term or quarterly outlook	Long-term outlook, 5 yrs
Only immediate high return	Low return acceptable
Little company loyalty or loyalty to suppliers	Strong company loyalty and loyalty to suppliers
Little co-operation with university research	Close co-operation with university research
Little government funding of company R&D programs	Government funds strategic R&D programs
Low savings rate/high interest rates	High savings rate/low interest rates

Manufacturing and Marketing Infrastructure

The United States has a fully developed infrastructure for manufacturing. The value added by manufacturing has been a true source of strength behind the U.S. economy. A major component of this strength is the ready availability of highly qualified industrial designers and manufacturers of automated production equipment. In general, the production by U.S. equipment designers and manufacturers is less expensive than their Japanese counterparts, and their equipment is equally good or better.

The U.S. battery companies have been successful in primary battery markets. Three of the world's five largest producers of primary cells are based in the United States. Most of their business is dedicated to supplying batteries to power simple portable electric devices. All have production facilities throughout the world with global marketing and distribution networks that deliver products directly to consumers through retail outlets. Success in the primary market has been dependent on establishing highly automated production facilities, as well as economies of scale, and marketing the unit cells directly to consumers using branding, advertising, and strong control of the distribution network. These are not key issues in the rechargeable market.

Success in the rechargeable market requires knowledge of the electrical requirements for emerging products that use batteries as well as the ability to generate rapid product improvements to meet the demand and then to assemble the unit cells into battery packs for use in the device. Most U.S. producers have lacked this marketing and design/production infrastructure.

Large Japanese vertically integrated, consumer electronics companies have this infrastructure in place. These companies are major players in both primary and rechargeable battery industries. European companies have manufacturing capabilities for primary and some rechargeable batteries, but are not globally oriented on the scale of U.S. or Japanese battery industries.

Duracell originally envisioned forcing the Li-ion cell into their business model for alkaline cells. They proposed and implemented a series of standard size packs for the industry to choose from, based on a minimum of different standard sizes, or stock keeping units (SKU), and sold through their regular distribution channels for notebook computers. The approach failed because the notebook and cellular telephone designers each had a unique layout, and considered it a critical product differentiator. Furthermore, computer manufacturers have a strong incentive to sell their own packs at the time of initial purchase because the packs are very profitable for them.

The past half century has seen a significant hollowing of traditional U.S. industry. In the global economy, engineering, design, and distribution can be located in the United States while manufacturing is conducted in Southeast Asia. However, once the production process is out of a company's immediate control, it often loses control of the intellectual property on which the manufacturing and product technology is based. New technology is now being developed in the countries to which the production had been shifted.

Duracell, Energizer, and Rayovac have acquired manufacturing facilities or formed joint ventures in China for alkaline cells. Eventually, using their strong worldwide distribution networks for primary batteries, they could well take advantage of the lower production costs in China and shift production of primary batteries there. These distribution networks are entirely different from those needed for the rechargeable battery business, which is one of the reasons Eveready and Duracell exited the rechargeable battery business. They all buy rechargeable Ni-MH cells from China and Japan for resale using their distribution networks.

Supply Chain Structures

Japanese companies are geographically closer to other Asian markets for selling their products, sourcing production, and working with other makers of portable devices. The Japanese battery supplier is most often part of a vertically integrated Japanese electronics company. Proximity to the device designer gives them a significant advantage in developing new products for the market. In the United States, major battery producers are “on the outside looking in,” with limited access to or understanding of the needs of portable electronic device manufacturers. Device manufacturers such as Motorola and HP do not share new product concepts and developments with U.S. battery manufacturers.

It is even more difficult for U.S. manufacturers to identify new battery requirements for devices that are being developed in Japan, the heartland of portable device developments. The Japanese market is not readily accessible to non-Japanese companies, making it very difficult for U.S. battery manufacturers to act as suppliers of the batteries for new products developed in Japan. As a result, the U.S. battery manufacturers were unable to take advantage of the introduction of the Li-ion battery to the portable device market in 1991.

We examined some of the structural differences underlying these different market relationships in the United States and Japan in greater detail.

The relationship of battery suppliers/manufacturers to the OEM manufacturers of portable electronic devices follows two patterns. In the vertically-integrated Japanese electronic companies, device designers and battery groups are equal partners in developing leading edge new products. The intensity of market competition in Japan has resulted in the recognition by both groups that having batteries of the highest capacity is critical to device sales. Designers of battery components have advanced notice of the needs of the device designers. They thus have time to develop a battery with special characteristics or offer an improved version of their present battery for incorporation into the device.

This coordination between device designer and battery manufacturer does not exist in the United States. Since new device designs constitute very sensitive business information, the device designer will not share detailed information on the battery needs with outside battery suppliers until the device is almost ready for production. Once new device designs are complete, OEMs specify battery requirements. They then use their specification to purchase from suppliers worldwide, based on price.

The relationship of U.S. battery manufacturers to device designers, including U.S. cellular phone, notebook computer, and other wireless manufacturers, is distant. The device designer imposes new product requirements. The device manufacturers develop relatively detailed battery performance specifications and buy against their specifications on price. They also want at least two suppliers of each component to have an assured supply to meet their needs. The battery manufacturers have relatively little advance warning when a new cell size is required for a new device. U.S. and European device manufacturers would buy a battery product from U.S. suppliers if it were available and the cost and performance were competitive.

All interviewees from U.S. battery manufacturers felt strongly that device designers place the battery last in their designs. The cavity provided for the battery is often an afterthought and undersized for the expected performance. It often does not fit particular battery sizes and shapes that are currently being manufactured.

The device manufacturers qualify battery suppliers and will conduct regular quality audits of the supplier's plants to ensure compliance with specifications. This contrasts markedly with the situation in Japan, where battery and device designers in the same or sister company work in parallel to arrive at new sizes or shapes much more efficiently.

The Japanese materials suppliers often have agreements with their customers down the supply chain to include some R&D activity to improve their products. In Japan, materials suppliers truly cooperate with battery manufacturers, whereas battery manufacturers in the United States typically have no continuing relationship with their materials suppliers. U.S. manufacturers often insist on having two suppliers for critical materials for their manufacturing operations.

A global market exists for battery materials. The same material can be purchased from several companies at the same price in the United States, China, or Japan. All of the major material producers for Li-ion batteries, however, are located in Japan. Although several U.S. companies are capable of producing all the components and materials, no viable market exists in the United States because there is little manufacturing here. Two U.S. materials producers have established a presence in Japan to supply the Japanese Li-ion battery manufacturing. Because of cultural barriers, these suppliers spent five or more years establishing a presence in Japan before the Japanese battery manufacturers would consider them as reliable suppliers.

As a result, U.S. battery manufacturers have no loyalty to U.S. suppliers for materials produced locally and will buy materials globally from the lowest-cost producers. One materials supplier emphasized that large U.S. battery manufacturers universally disallow the materials supplier sufficient profit to invest in process improvements, or, more importantly, to develop new materials for a next generation product. As a result, materials producers are reluctant to invest in additional R&D to develop a new technology. They will pursue engineering improvements only to meet performance requirements. These differences in supply-chain relationships in the United States and Japan place U.S. OEMs at a considerable disadvantage in addressing markets using rechargeable batteries.

R&D Planning Horizon and Return on Investment

U.S. companies often have a very short-term outlook that results from the common practice of linking management compensation to the company's stock share price. There is a strong corporate drive to have immediate profits match forward stock analyst projections, and bonus systems often reinforce this tendency. The stock market responds directly to the profitability of the company on a quarterly basis. When a performance bonus is included in the management compensation package, fluctuations in stock price can directly impact remuneration for executives. Managers in the United States receive bonuses that often are equal to or larger than their base salaries. Since R&D expenses negatively impact the net earnings for each quarter, managers may tend to sacrifice R&D in order to maximize their immediate income and company earnings, and may be reluctant to invest in new facilities that have a longer-term payback than one or two years. The financial impact of the introduction of new products is not felt in company profits until three to five years in the future, which is often beyond the horizon of personal benefit for the U.S. manager.

In contrast, Japanese managers generally take a long-term outlook, and their goal is to gain market share. They aim to ensure that the company will be in good condition when they hand it off to the next generation of managers; thus, their outlook is five years or more. This gives them the opportunity to invest significantly in future R&D for product improvements. Japanese companies report earnings on a yearly rather than a quarterly basis. This means that a company has two years to recover from a down period, and that the managers are not pressed for immediate profits. When a market matures, the companies with the largest market share profit, second-class players survive, and third-place players disappear. The availability of bank loans at low interest rates in Japan reduces the pressure on managers to focus on profits and stock price.

The large, well-funded battery manufacturers in the United States have discontinued in-house funding of forward-looking research and development. They now tend to fund only R&D that is related to performance improvements in their current products. If needed, they believe that new technology can be acquired from other companies, particularly from venture-backed companies, which generally lack the ability to generate sufficient capital funding for production capability. The battery manufacturer often has a powerful engineering group with expertise in the design and operation of automated production. Most venture operations lack this critical expertise. New technology the battery company acquires must have the potential to produce immediate impact on the bottom line, with a recovery of investment in two years or less, and ideally the new technology can be adapted to present production equipment.

In existing companies, new technology that departs from the current product line must present a truly significant business opportunity to justify funding of new facilities. An interviewee with a materials company said that the company would invest in new equipment for producing a new product only if one of its customers would commit to a purchase order for a given amount of the new material (basically guaranteeing a portion of the initial investment). Generally, a similar process is involved if a device manufacturer wants a specialized cell for its device. The battery manufacturer will want a guarantee from the customer to purchase a minimum amount of the specially-designed product.

Project and Employment Security

Since Japanese battery manufacturers are invariably part of large, vertically integrated electronics corporations, their device designers and battery developers readily share new product information. Early in the product development cycle, the battery group has inside information on the new requirements, sizes, and performance specifications. Conversely, the device designer is aware of attainable capabilities for battery performance. Each has time to respond to the evolving needs of the other. Where executive bonuses are not strictly tied to the price of stock, management compensation is not threatened by the vagaries of the stock market. This results in greater security for R&D programs. Japanese companies rarely suffer staff reductions, and the managers are relatively free to engage in long-term planning.

Replacement Market

The distribution channels that Duracell and Eveready have established for battery sales, which are based on selling individual cell units to the consumer, are not applicable to Li-ion batteries. Because of safety and performance considerations, Li-ion manufacturers (except those in China) do not sell individual cells. Japanese cell manufacturers sell only battery packs with safety devices included. A battery pack can consist of a single cell, or multiple cells connected in series or in parallel, to give the required voltage and capacity. Individual cells from major Japanese manufacturers are available only to outside pack assemblers on approval of their electronic control circuitry in the pack. Individual cells are available from Chinese manufacturers, but are often of inferior quality. They often lack the usual safety features in cell design and electronic controls and thus constitute some danger to the public. This is not true for responsible manufacturers who try to match the world standard of performance.

The replacement market for Li-ion cells is minimal. Of the purchasers of a new piece of equipment such as a cell phone or a notebook computer, about 30 percent will buy a second battery pack from the OEM. After that, replacement sales account for less than 2 percent of total battery sales. People typically buy a new, higher performance notebook computer about the time that their old battery would need replacement. Lower cost, knock-off replacement packs are available from many Internet suppliers, such as IGO, at about 50 percent of the cost of the original pack. The knockoff packs may not have the same safety circuitry as the original packs, and could be dangerous in actual operation. Nonetheless, many people buy these knockoff replacements.

Logistics

Materials and components for the manufacture of Li-ion batteries are readily available any place in the world for essentially the same price. In addition, Li-ion cells have a high value and are lightweight and small. The cost of shipping cells to pack manufacturers, wherever they are located, and then to the device assembler for incorporation into the final product, is not a determining factor in locating a manufacturing facility. In the global economy, the location of manufacturing operations is determined by considerations other than logistics.

Most Li-ion battery pack assembly, however, is located in Southeast Asia, because of the low cost of labor for manual operations. It is advantageous for the battery manufacturer to be close to the pack manufacturer when introducing new technology, or when a safety incident occurs. In these situations, the pack manufacturer needs a quick response from the battery manufacturer to identify and remedy the cause of the incident.

Venture Capital

Venture capitalists, consistent with the payoff requirements of OEM's, have likewise not found the time frame for development of rechargeable batteries acceptable. Success in commercializing battery technology at companies funded by venture capital has been spotty at best. The inability to generate sufficient income from product sales in an acceptable time frame has led to some failures. Venture-funded Valence Technology raised substantial funding through stock offerings and had a clear path to commercialize its technology, but sales have been disappointing. Venture-funded Bolder Technologies and PolyStor fell short of full commercialization of their technologies because of insufficient funding for production facilities. The companies were not able to translate good technology into practice within a time frame acceptable to venture capitalists.

One exception is PowerStor, a spin-off from PolyStor, which developed ultracapacitor technology under an ATP award, and then managed to have the manufacture of its products accomplished by hand in Malaysia. This choice required minimal capital and quickly resulted in product sales. The company eventually was acquired by California-based Cooper Electronics, a maker of audio equipment.

Many venture groups tend to follow the behavior reported in these examples. They will fund technology development to the point of proving its validity and defining the market. They are reluctant to fund costly manufacturing facilities or cover lengthy scale-up/“prove-in” procedures. The companies must raise funds for manufacturing equipment by stock offerings, license or sell themselves to an existing company, or go overseas to manufacture with a minimum expenditure.

Company Loyalty

Often U.S. employees have little feeling of company loyalty, and the company feels little, or no, responsibility for the future welfare of its employees. This contrasts with the traditional paternalistic company in Japan, which has engendered strong company loyalty with its system of lifetime employment. Although this lifetime employment system has never been universal in Japan, and has eroded in recent years, it is still prevalent for those who graduated from the best universities and who are now employed by the most prestigious battery companies.

Labor Costs

Although labor costs do not appear to play a significant factor for a highly automated Li-ion battery factory, they do play a significant role in the decision about where to place battery pack assembly. Where U.S. firms employ offshore activity for assembly, it helps build technical capabilities of Asian engineers and scientists, resulting in stronger capabilities by Asian firms, and increased offshore activity by U.S. firms in the longer term.

Several interviewees who were involved in developing Li-ion technology pointed out that the costs for skilled labor in a well-automated Li-ion factory (producing three million or more cells per month) are essentially the same in the United States and Japan. Production in this type of factory involves a minimum of hand operations, and skilled operators are required to ensure proper operation of the equipment. In such an automated factory, the material costs are 75 percent to 80 percent of total manufacturing costs (or higher). The volume of materials required to operate a plant of this capacity motivates producers to obtain the lowest price for a given material.

Labor costs are significant for battery pack assembly, as a considerable number of hand operations are involved in assembly operations. Small volume production items are especially sensitive to labor costs. As the president of U.S. operations for a Japanese battery company noted, most battery companies have moved pack assembly operations from Mexico to exploit the lower labor costs in China and Southeast Asia. Low volume niche markets can be serviced in the United States, provided that the higher costs for unskilled labor can be recovered.

This movement (product lifecycle) of manufacturing operations offshore has an additional effect. As local engineers and managers become skilled in working with the technology, they develop the capability to undertake process improvements themselves. This scenario has occurred in several semiconductor fabrication operations that moved to Taiwan 15 years ago. The local group now generates all the process improvements, independent of the U.S. parent company. This same outcome can be expected for battery operations that move to the East Asian countries. Although the basic technology still resides in the United States, with the relocation of manufacturing to Southeast Asia, the local operators and managers will learn the technology and eventually acquire the skills to improve it without aid from their U.S. counterparts.

A significant increase in the publication of battery-related technical papers from China and Korea has occurred over the past five years. Today, these contributions are of high quality and demonstrate a grasp of the fundamentals that previously were found only in papers by researchers from Europe and the United States. Many of these scientists were trained at U.S. universities and then returned to academic and industrial positions in their home countries.

This increase in technical capability is due to the strong government support in China and Korea, both for developing battery production facilities and for university research. China recently announced a program related to the 2008 Olympics involving production of electric vehicles powered by fuel cells and batteries. Production facilities for these vehicles will be located primarily in China and Korea. These countries offer large financial incentives in order to acquire technology expertise and establish domestic manufacturing facilities that provide jobs. Key technologies include power sources for portable electronic devices. The incentives usually involve a government loan or grant to a local company for the production facility, with an American or Japanese company providing the technology through a joint venture. As a result, the technology becomes resident in the host country. Historically, the company providing the technology is eventually forced out of the venture. There are incentives for the U.S. and Japanese companies, however, to try and obtain market share in China by having a presence there.

Capital Costs of New Facilities

Manufacturing facilities for Li-ion batteries are expensive. The rule of thumb developed for the cost of automated Li-ion facilities is that a volume manufacturing facility of three million cells per month has an annualized cost of $3 to $4 per cell. A plant making three million cells per month will thus cost between $108 and $144 million. This number includes the cost of the land, but not the costs for the research, development, and engineering (RD&E) that produced the technology and equipment designs for the plant. Plant costs are about the same worldwide.

The high cost partly results from requirements for high precision and environmental controls. In the United States, the permit process for new operations is slow and expensive. Contributing factors include the amount of paperwork companies must file to comply with EPA rules and regulations, as well as potential local political opposition to the location of new manufacturing facilities.

New facilities to produce the active materials for carbon anodes or oxide cathodes are less expensive to build than are those for cell manufacturing. Building new facilities for volume production of these materials will cost about $10 per pound for a facility designed to produce 1,000 tons of product per year. The cost of building new facilities is about the same for both carbon anode materials and cobalt oxide cathode materials. The cost of modifying and expanding an existing facility is slightly less, but still lies in the range of $1 per pound annualized. Materials companies traditionally operate on lower rates of return than do the battery companies. Material suppliers invariably prefer to modify existing facilities to produce a new product rather than build a new facility. Materials companies will not undertake the building of a new production facility without having agreements in place from customers guaranteeing to buy a specific amount of material.

In their return on investment calculations, U.S. managers must load their overhead from corporate staff as well as recovery of the investment in a 3 to 5 year frame. At the time the Energizer group made its decision to cancel its Gainesville Li-ion plant, the calculations showed that the returns from the new plant would be much lower than for alkaline cells. Further, based on the required calculations, Energizer could buy the cells cheaper than they could make them.

R&D Costs

Ten to fifteen years ago, the large battery companies pursued significant R&D efforts. Today, these same companies engage in little or no basic research and have practically eliminated forward-thinking product R&D. Internal funding of R&D is most often directed toward improvements in present products, and research work now consists entirely of applied development, with little emphasis on basic research. If needed, these companies expect to buy new research concepts and technology developed elsewhere.

Advanced analytical instrumentation is essential to advance a research program. Instrumentation costs include both hardware and skilled labor. The cost of equipment for Li-ion R&D is significant. The initial acquisition of ESCA-Auger analysis equipment costs $750,000 or more, and a good mass spectrometer gas chromatograph costs from $250,000 to $300,000. In three or four years, personnel costs for dedicated operators can equal or exceed the cost of the equipment. Only a few well-funded battery R&D operations, such as those at Telcordia, Duracell, and Eveready, can afford advanced analytical equipment and the personnel to run it.

Use of university facilities is a possible solution. Most R&D labs are near university facilities that have a collection of advanced analytical equipment, such as ESCA-Auger, mass spectroscopy-gas chromatography, transmission electron microscopes, and surface Raman spectroscopy. Private companies can pay to use these facilities. Most universities require scheduling use of facilities by outside companies, however, and researchers must travel to the university to carry out the analysis.

In general, companies find using university facilities to be inconvenient, time-consuming, and expensive. Researchers are under time pressure to obtain results. They do not find it efficient to wait a week and travel for 30 to 60 minutes to spend a short time on the machine and obtain a single result. They would more likely use such equipment if it were down the hall or across the street.

Interest Rates

Even though interest rates are at historical lows in the United States, the cost of securing money for business investment continues to be lower in Japan. The low interest rates in Japan are driven, in part, by the higher savings rates. People in Japan have been saving an average of over 20 percent of their gross income annually. In contrast, the personal savings rate in the United States dropped from about 8 percent in 1990 to become slightly negative in 2000. The Japanese tend to save more money than Americans for their retirement. This high personal savings generates large amounts of capital available for loans and investment in Japanese banks, resulting in low interest rates for commercial loans.

Low interest rates in Japan often encourage Japanese companies to rely more on bank loans to fund R&D and new production facilities. This is in direct contrast to the financial resources available to U.S. companies from lending institutions to build new facilities and the actual costs they would incur.

Intellectual Property

Intellectual property (IP) consists of patents and know-how that a company possesses. The importance of IP in the battery environment depends on the company's role in the marketplace. A venture fund company must have a unique IP position in order to generate funding for the venture. It is important to build a group of patents around the core technology to protect the area of interest from outside predators. Investors believe that patent protection of the technology is the key to success. Uniqueness in a venture operation is an essential element.

A strong IP position can protect a market. Energy Conversion Devices Corp. (ECD) has been very successful in keeping Ni-MH batteries under control of its patents. No one can import Ni-MH into the United States without taking a license from ECD. This generates considerable income for the company. Another example is the patent for lithium cobalt oxide ($LiCoO_2$) for use in batteries. Harwell, in England, controlled the use of $LiCoO_2$ in Li-ion batteries until the patent expired in 2002. All Li-ion manufacturers have taken a license on this patent, generating significant income for Harwell. Composition-of-matter patents can be very important as they are easily defensible. They have played a key role in R&D related to Li-ion systems, and in other battery systems as well.

Intellectual property is less important for existing battery manufacturers. Although they view IP as providing the freedom to operate, they see manufacturing process technology and know-how as the real keys to low cost production and survival in the market. To meet requirements for new products, they believe that they can acquire or generate IP as needed. In the past, R&D efforts have developed considerable IP for new products.

Energizer's plans for Li-ion production included both its own and acquired IP, and the acquisitions were accomplished prior to their building their Gainesville plant. They licensed a core Goodenough patent from Sony and intended to purchase materials from companies that had an IP position on the particular form of carbon/graphite they intended to use. The license on the carbons came with the purchase of the materials. They had developed their own IP positions in several areas such as sealing and venting that would make their cell construction safer and better than the competition.

Litigation Exposure

Another difference between the United States and Japan is the difference in legal exposure companies experience in regard to various product safety incidents. The most common incident involves a cell in a battery pack entering thermal runaway and venting with fire. This usually causes significant damage to the notebook computer or other device. According to the VP of sales of a materials company, this legal exposure presents a considerable risk for makers of Li-ion batteries specifically, and those introducing new materials and technology in general. In the United States, such incidents are cause for class action lawsuits against the offending company. Japanese companies in their home market deal quickly with the individuals involved in the incident. They do not rely on their legal system to provide reparation. The Japanese approach of proactively providing reparations and demonstrating human concern reduces their legal exposure in their home market. In contrast, for a U.S. company to demonstrate concern for the victim of an incident would be an admission of guilt, potentially exposing itself to additional legal repercussions.

About five safety incidents involving notebook computers occurred in 2002. Cell production was in the range of 770 million units, of which roughly 40 percent (350 million) were for installation in notebook computers. This translates into 5 incidents in 308 million, or slightly more than 1 in 61 million cells. Cell manufacturers are working hard to improve the odds. The manufacturers of cellular phones and notebook computers accept the current rate of incidents as a cost of doing business. Although safety is still a concern for the cobalt cathode cells, recalls resulting from safety related incidents have not increased in spite of a significantly higher cell capacity and increases in production.

Government Policies

Government policy can encourage or discourage plant locations. The relationship between government and industry in the United States differs from that in other countries. In the United States, the government more frequently takes an adversarial position against industry on environmental issues. Government and industry are more likely to turn to the courts to resolve problems. This is in sharp contrast to the cooperation between government and industry in Japan and elsewhere where the two groups work together to solve problems as quickly and expeditiously as possible.

The Japanese government works with industry to identify new technologies that are ripe for near-term economic exploitation. Government then encourages companies that will eventually be competing with each other to share information and cooperate during the early stages of research and development. This contrasts with the U.S. pattern of business-government relations, where such cooperation is deemed anti-competitive under some conditions.

In Japan, the government funds strategic research initiatives with the participation of industry, universities, and government to develop new materials and Li-ion battery constructions for new applications. These initiatives often involve scientists and engineers from several companies and universities, along with government laboratories. The people in these programs meet regularly to discuss progress and plan the next activity. They freely exchange information and results.

In South Korea and China, among other countries, the government will loan companies the funds to establish automated manufacturing facilities to produce Li-ion and Li-ion polymer batteries. These loans are often made at low interest rates, and may be forgiven if a certain level of production is reached. Countries such as Northern Ireland and Singapore offer incentives to establish essential strategic research, development, and manufacturing for advanced batteries on their shores. For instance, Valence Technology received up to $40 million in matching funds from the United Kingdom to establish a manufacturing plant in Northern Ireland. The agreement included conditions and goals relating to the number of employees, the amount of production, and the like. These arrangements are powerful enticements for U.S. companies to move production abroad.

Compared with Asian countries, the United States makes little funding available to assist companies in addressing longer-term research. The Advanced Technology Program is an exception to the pattern, with its mandate to initiate change by offsetting some of the costs of technically risky, longer-term research with potentially broad national benefit. However, its resources are small.

With the exception of its relatively small funding through the ATP and Small Business Innovative Research (SBIR) programs, the U.S. government essentially does not fund research with a commercial purpose, and U.S. companies seldom fund university research because the university would generally require ownership of all resulting intellectual property (IP), regardless of the source of funding. ATP's focus is on cost-sharing industry-led projects with strong commercial potential. ATP has funded $2.3 billion in advanced technology development, with industry cost sharing an additional $2.3 billion in their ATP projects. The ATP also fosters collaborative R&D among suppliers and manufacturers and with universities. More than four out of five projects involve collaboration among multiple organizations. About three out of five projects have university participation. Over one out of four projects is an industry-led joint venture.

The Department of Defense and the Department of Energy support most of the U.S. university research on new battery materials. Most of this research is for military applications, however, complicating the transfer of the technology developed in these programs to industry. Only a few small manufacturers are dedicated to such niche military markets. The U.S. Auto Battery Consortium (USABC) and its survivors do not fund pure research, per se. In spite of investments in excess of $200 million, none of these programs has produced a new commercial battery. Although support exists for battery-related R&D at the national laboratories, these laboratories have little direct connection to battery and materials companies that would commercialize the results.

Many new products developed by Japanese companies are derived from university research supported by company funding. The Japanese government funds strategic R&D programs involving people from universities as well as from companies. The information is shared with all those involved in a particular program. Because of antitrust considerations, it is difficult and unusual for U.S. companies to engage in information-sharing outside of government-sponsored R&D consortia projects, such as those funded by ATP.

Human Resources

Essentially all interviewees agreed that qualified people are the key element to technology development and transfer to production. The number of qualified research people in the battery industry is limited. A large number of highly qualified materials scientists graduate from universities but are not specifically trained for industrial research in battery technology. Often these students have been trained in basic research, but not in applied research, and often they lack the skills or philosophy required for applied research. Battery companies expect to spend an additional two to three years training new hires before they can work effectively in an industrial environment.

Industrial recruiters look for individuals with experience in electrochemical materials research—those who are self-starting, creative, and, as demonstrated in thesis work, have a capacity for unorthodox thinking. Characteristics for new hires include that they must be willing to work on a team for a common result, not be adversarial, and not feel threatened. They must be capable of expressing themselves and their opinions clearly in give-and-take discussions.

V. Conclusion: Why Are There No Volume Li-ion Manufacturers in the United States?

Dramatic growth in the rechargeable battery market during the 1990s and into the new century has been dependent on a number of factors. These include:

- the exponential growth of the portable electronic product market sector;
- the ability to introduce improved rechargeable battery technology and rapidly ramp up production levels to meet demand;
- delivery of high quality and safe products, competing on market share over margins;
- the openness of non-vertically integrated portable computer and cell phone producers;
- strong product OEM relationships; and
- aggressive price reductions throughout the industry.

The major U.S. battery producers were not well positioned to compete along these factors. The competition from Asian companies caused most major North American rechargeable cell manufacturers to strategically exit the business. The U.S. battery companies "opted out" of volume manufacturing of Li-ion batteries, primarily because of a low return on investment compared to their existing businesses. Battery technology requires significant time and investment from conception to commercialization. An important consideration for U.S.

battery manufacturers was the time and expense required to establish a sales organization in Japan to access product design opportunities. One Japanese interviewee reported that the Americans just gave up the fight.

Interviews conducted with numerous U.S. companies suggest that the U.S. companies missed the growth curve. Japanese companies gained considerable "first-to-market" advantage in obtaining high prices and profits initially. By the time U.S. companies decided to begin commercialization, prices for cells were dropping. U.S. companies had not anticipated the rapidity with which the Japanese companies would develop and commercialize Li-ion technologies.

According to one U.S. VP of technology, their financial analysis indicated that they could produce cells in the United States for essentially the same cost as their Japanese counterparts. The analysis also showed, however, that the profits delivered by the Li-ion venture would be significantly lower than that delivered by their alkaline cell business. Thus U.S. companies were unwilling to tolerate the market pressure for quarterly profits and lower personal bonuses, in order to invest in the future. In contrast, Japanese companies sought market share rather than short-term profits and were more willing to make investments for the longer term.

Also contributing to the decision-making environment were structural differences between U.S. and Japanese business environments. For example, for U.S. companies, marketing costs were higher for rechargeable batteries than for alkaline cells. Since most device designers and customers were located in Japan, U.S. companies would need a strong sales effort to compete overseas, especially in Japan. Establishing a presence in Japan for a company generally requires five to seven years of intense activity to be effective. In-house utilization of Li-ion batteries by the vertically integrated Japanese consumer electronics companies functions as a trade barrier to U.S. companies seeking to do business in Japan. In the absence of an American version of the Japanese vertically integrated consumer electronics company, U.S. battery producers might have teamed up with U.S. manufacturers of cell phones, notebooks, and other portable devices, such as Motorola, Dell, and HP (now including Compaq), but did not. In a short period of time, the U.S. companies exited the business.

Labor costs were not a critical or deciding issue, as the cost to produce cells in the United States was essentially the same as for the Japanese manufacturers. The Asian strategy of providing facilities and loans to establish local manufacturing and create jobs at home proved more important. On the other hand, labor costs were instrumental in locating battery pack assembly plants, with repercussions ultimately for higher-valued processes.

Structural differences of Japanese electronic products industry compared with its U.S. counterpart create barriers to U.S. firms seeking to market rechargeable batteries or battery materials in Japan. In markets for rechargeable batteries, customers are large, high-technology-based electronics companies, typically having Li-ion production within the same company. Developing a product requires close contact with portable electronic device designers.

Huge investments have been made in Japan, Taiwan, South Korea, and Southeast Asia in a global effort to capture the market for rechargeable batteries for telecommunications, wireless, and computer products. The magnitude of the investment in Asia has been such that the United States progressively has lost its technological position, despite the fact that U.S. and Canadian researchers provided many of the critical technology breakthroughs required to establish the technical feasibility of the currently pre-eminent Li-ion polymer battery. North American companies failed to capitalize on this early technological leadership, and Asian companies have since established a dominant position in the production of

Li-ion polymer batteries. The United States has become an incubator for new technologies and materials for rechargeable batteries, while the Asian companies have developed the manufacturing expertise and capital facilities to profit from the technology and build their presence at home.

The United States still leads in developing new technology and is the major source for new concepts in battery, fuel cell, and display technologies. In a real sense, the United States has become an incubator for new technologies relating to the electronics industry, while Asian and European companies are developing the manufacturing expertise. In Korea, KIST, the Korean Institute of Standards and Technology, has a goal of transferring the good technology ideas developed by small U.S. companies to the large Korean manufacturers. Similarly, most large Japanese producers maintain a technology surveillance unit in the United States to identify promising new technology for use in their new products.

The tendency may be for technological development to follow manufacturing in moving to East Asia. This would be a natural consequence of East Asian companies' developing manufacturing expertise. Primary as well as rechargeable battery production may slowly shift to China, Korea, and Southeast Asia following Japan's initial lead in rechargeable battery production. U.S. manufacturers pursuing other budding energy technologies, such as fuel cells, will face similar issues. Opportunities still exist for companies to successfully enter niche markets, such as those with medical, military, or space applications.

VI. Implications for Other Technologies

To what extent are the factors affecting U.S. production decisions by the battery industry common to other U.S. industries? And what are the implications, particularly for budding energy technologies, but also for more mature electronics industries, such as flat-panel displays, which have been migrating offshore for some time?

Fuel cells

To avoid erosion of technological and economic leadership, North American companies will need to make sufficient investments to build the infrastructure for successful commercialization of emerging energy technologies. The findings of this study concerning Li-ion battery technologies can be applied directly to fuel cells. The U.S. government has identified fuel cells as a means to reduce dependence on imported fossil fuels. Development efforts in fuel cell technology are divided into three applications: 1) small power sources for portable electronic devices; 2) larger units for transportation; and 3) stationary power for providing electricity for buildings and homes on-site. Of these, stationary power generation demonstrates the most significant potential market. Viable market applications include uninterruptible power supplies to maintain critical processes that are intolerant of power interruptions. Fuel cell applications in portable electronic devices offer the strongest parallels to Li-ion batteries.

All Asian and European manufacturers of portable electronic devices have fuel cell programs. These companies have representatives in the United States that closely follow the technology developments on the U.S. scene while planning their own product development.

Fuel cell applications in portable electronic devices, specifically direct methanol fuel cell (DMFC) technology, have the strongest parallels to Li-ion batteries. The status of developing DMFC technology for small portable electronic devices clearly falls into the development phase. The electrolyte membrane needs improvement, the cost of the platinum-rhodium catalyst loading is too high, and the best cell configuration has not yet been determined. Furthermore, the best concentration of methanol is still being explored. This fuel cell technology is ready to transition into advanced development, which constitutes the first step toward commercialization. This stage requires a considerable investment in equipment and pilot facilities for assembly and testing of the DMFC prior to manufacturing. The present cell designs vary from one company to the next, and some aspects of their production lend themselves to hand assembly rather than automated production. Some phases of production can be automated; for example, roll-to-roll facilities must be designed and implemented.

Approaches representing a significant departure from present practices appear to have a chance for market success. For example, Neah Power, Inc., is pursuing a silicon-based fuel-cell technology. This shows some promise. The work of MTI under the auspices of an ATP award is making progress using pure methanol to avoid some water management problems. They have demonstrated a cellular phone charger.

It is impossible to predict with certainty what route fuel cells will take to commercialization. The fuel cell developers with deep pockets can afford to develop automated cell assembly. Once equipment design begins, it generally takes 18 to 24 months to commission a plant. If funds are unavailable, or if there is a rush to market, companies can be expected to explore hand cell assembly in Southeast Asia or China, as opposed to automated assembly in the United States, thereby taking advantage of low labor costs and minimizing investment in equipment. In this scenario, production can begin with a minimal investment in tooling and increasing production is just a matter of adding hand tooling and more people. Manual production results in greater variability in product quality than with automated production, but is generally acceptable with proper quality control.

At the present time, no U.S. company has committed to volume production of DMFC fuel cells. Although Motorola announced two years ago that it would have a methanol-based fuel cell in two years, they recently reduced their efforts and no longer have a timeframe for introducing such a product. All work is in the advanced developmental stage. An interviewee who works for a Japanese electronics company that has its own fuel cell program expects that the U.S. developers will not manufacture in the United States, but rather in Japan, Southeast Asia, or China. Several Asian companies appear to be close to commercialization, including Samsung, NEC, Casio, and Toshiba. NEC exhibited a DMFC-powered notebook computer at the WPC EXPO 2004. The date for their commercial introduction has not been set.

Micro fuel cells, as well as larger stationary units, in particular, have a window of opportunity to start manufacture in the United States.

Displays and chip fabrication

Commercial development of other technologies, such as displays and chip fabrication, can be expected to follow the same pattern that has applied to Li-ion batteries and might apply to fuel cells. Manufacturing in the United States will require investment in automated production. With such automated production, it is possible to produce high quality products at competitive costs. Like the structural advantages Asian firms enjoy at home in the Li-ion industry, similar advantages will be present for Asian companies in domestic display and chip fabrication production. The United States still enjoys the lead in chip manufacturing, where U.S. companies made a substantial investment following their lead in technology development. Assembly into electronic devices is now predominantly off shore, by U.S. and Asian OEMs.

The Japanese automobile companies have established a clear lead in developing hybrid gas-electric cars (HEV) using a Ni-MH battery for electrical power and regenerative breaking. Their second generation vehicles have substantially improved performance and are in the market. In the meantime, they are developing new low cost-high power Li-ion batteries for the next generation vehicles. Although government funded research on new materials in the United States has developed new high performance–low cost materials, no U.S. Li-ion battery manufacturer is positioned to supply this developing HEV market.

Further Work Needed

ATP and other agencies recognize that investment in research and development of new technologies entails considerable business uncertainties as well as technical risks. For many technologies, pathways to economic benefits for the United States will entail additional complexities as portions of the commercialization process occur offshore. A successful investment strategy will include realistic appraisal of the likelihood of commercialization:

- in the United States;
- by U.S. firms abroad; and
- by non-U.S. firms where U.S. industry and individual consumers are significant beneficiaries.

The current study is an effort to identify some key factors in decisions to engage in offshore production in the commercialization of rechargeable battery and related technologies. Additional in-depth study is needed to explore specific pathways and to quantify benefits to the United States where significant commercialization activity occurs offshore.

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Appendix 1. Interview Questions and Discussion Topics

Broddarp of Nevada designed and administered the following questions to 40 individuals representing over 35 organizations, including major battery companies, materials and component suppliers, the military and government, venture capital and start-up companies, intellectual property experts, OEMs, and universities.

- Why are there no large volume Li-ion or other advanced battery manufacturers in the U.S.?
- Identify the factors affecting the introduction of new rechargeable batteries in the United States. What are the barriers to commercializing new battery technology?
- What are the business strategies (industry) and policy mechanisms (government) that relate to these issues?
- What are the implications for selection and funding for projects in the fuel cell area?
- Assess relevance of these findings to other electronic-material technologies, e.g., displays and consumer electronics.
- Consider new initiatives in national policy and business strategies to address these problems.

These questions were asked in the context of broader discussion of the following topics:

- General industry characteristics for success in incorporating new technology (*How do you recognize that a technology is ready for commercialization?*)

- Impact of labor costs (*Type of production, mass or niche*)
- Capital costs for new facilities (*Cost per cell, cost per ton for a new product and its impact on decisionmaking*)
- Existing manufacturing infrastructure on a global basis (*Importance of support structure and its availability*)
- OEM requirements and philosophy (*Customer requirements for supply of product; how to identify new product opportunities*)
- Replacement market (*OEM vs. consumer, relative size*)
- Intellectual property issues, competitive technology advantage (*How important for new product vs. improvement; venture vs. current manufacturer*)
- Logistics considerations (*Shipping costs, etc., plant location, transportation of supplies*)
- Government policies (*Effect on decisions, changes to encourage new product development*)
- Investment in R&D and in new equipment (*In-house vs. purchased, major analytical items*)
- People impact — characteristics of for successful implementation (*Availability of qualified personnel, type, how to identify, etc.*)
- Other

Appendix 2. List of Organizations Represented in Interviews

Listed below are the companies, universities, and federal laboratories represented by our interviews. In some cases, we interviewed multiple individuals, representing different functions.

- A123
- Argonne National Laboratory
- B.F. Goodrich
- Blomgren Associates
- Carus Chemical
- Cooper Electronics
- ECD
- Energizer (active and retired individuals)
- Eltech (retired individual)
- Engineered Power
- Duracell (active and retired individuals)
- Ferro
- FMC
- Gaia
- General Motors
- Gillette
- H Power
- INCO Specialty Products
- Inspired Energy
- Kerr McGee
- MIT
- MTI Micro
- Panasonic

- Petoka
- PowerSmart
- Sion Power
- Superior Graphite
- Telcordia
- Texas A&M
- TIAX
- Toshiba (retired individual)
- Ultralife
- U.S. Army
- University of Texas
- Valence Technology
- Venture

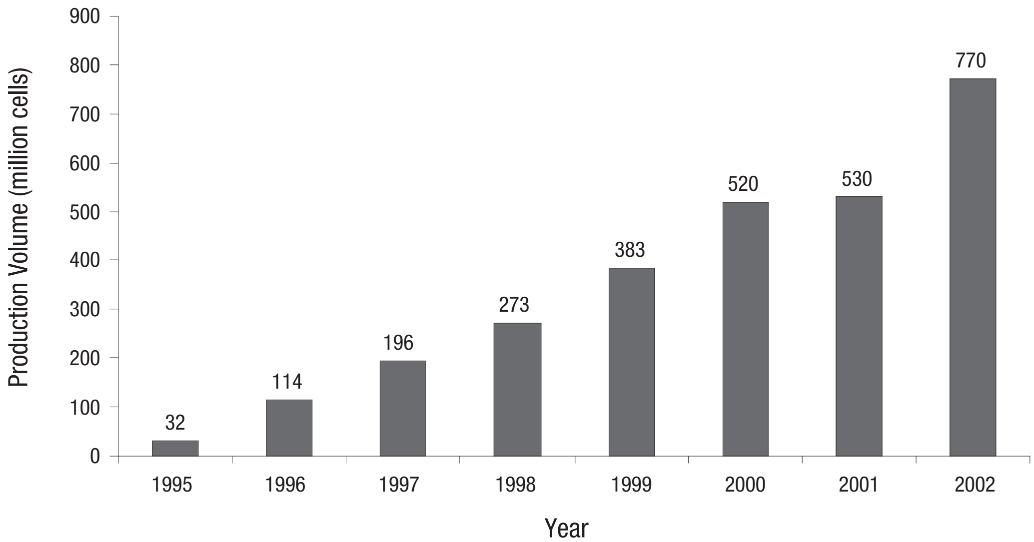
Appendix 3. Li-ion Batteries: Market Trends

In the 1990s, sales of Li-ion systems experienced an annual average growth rate of 15 percent or more. This rate slowed during the 2000 to 2001 time period. Current forecasts call for the Li-ion segment to grow between 5 percent and 10 per year in unit sales, but it is expected to show little growth in value during the first decade of the new century. Figure A3.1 summarizes production trends for Li-ion batteries, as assessed by Cambridge, MA-based Tiax.

As shown in Figure A3.2, prices for cylindrical cells have declined considerably over the past ten years. At their introduction, Li-ion cells sold for almost $4 per watt-hour (Wh). By 1995, the price had fallen to the range of $1.50 to $2.00/Wh. The pricing had some differentiation between cylindrical, prismatic, and polymer cell constructions, with polymer and prismatic cells commanding a higher price. As the production volume grew and competition increased, production exceeded demand and the selling price for cells decreased dramatically. The prismatic and polymer systems have maintained somewhat higher price levels than the 18650 cell, which is an industry standard used for comparison purposes.

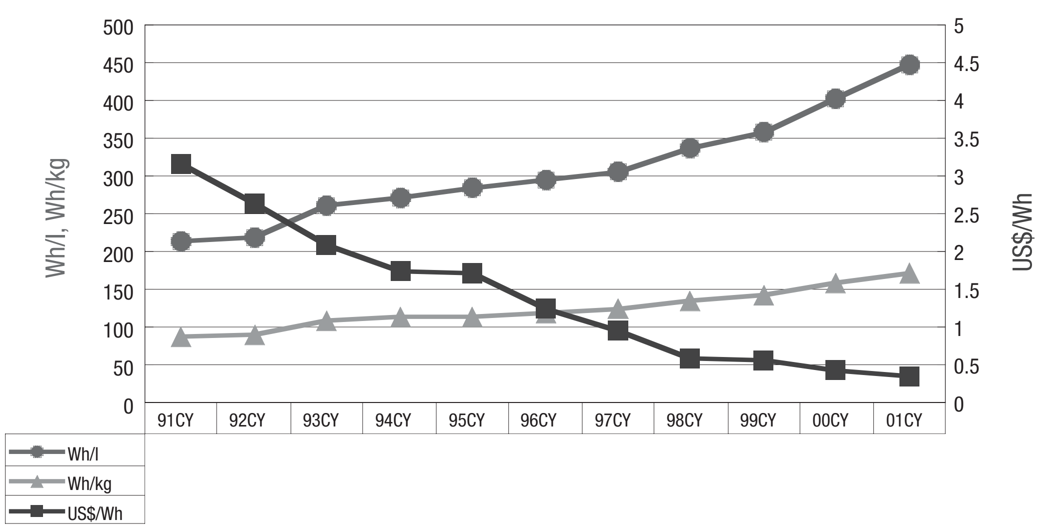
Since their introduction in 1999, Li-ion polymer cells have demanded a higher price than other rechargeable batteries. The perceived value and lighter weight of the polymer electrolyte, give the Li-ion polymer cells greater commercial value. Initially, production costs were higher for Li-ion batteries, as they required new production equipment, whereas

Figure A3.1. Worldwide Production of Li-ion Cells, 1995 – 2002



Source: Tiax.

Figure A3.2. Performance and Price Erosion in Li-ion Market, 1991 – 2001



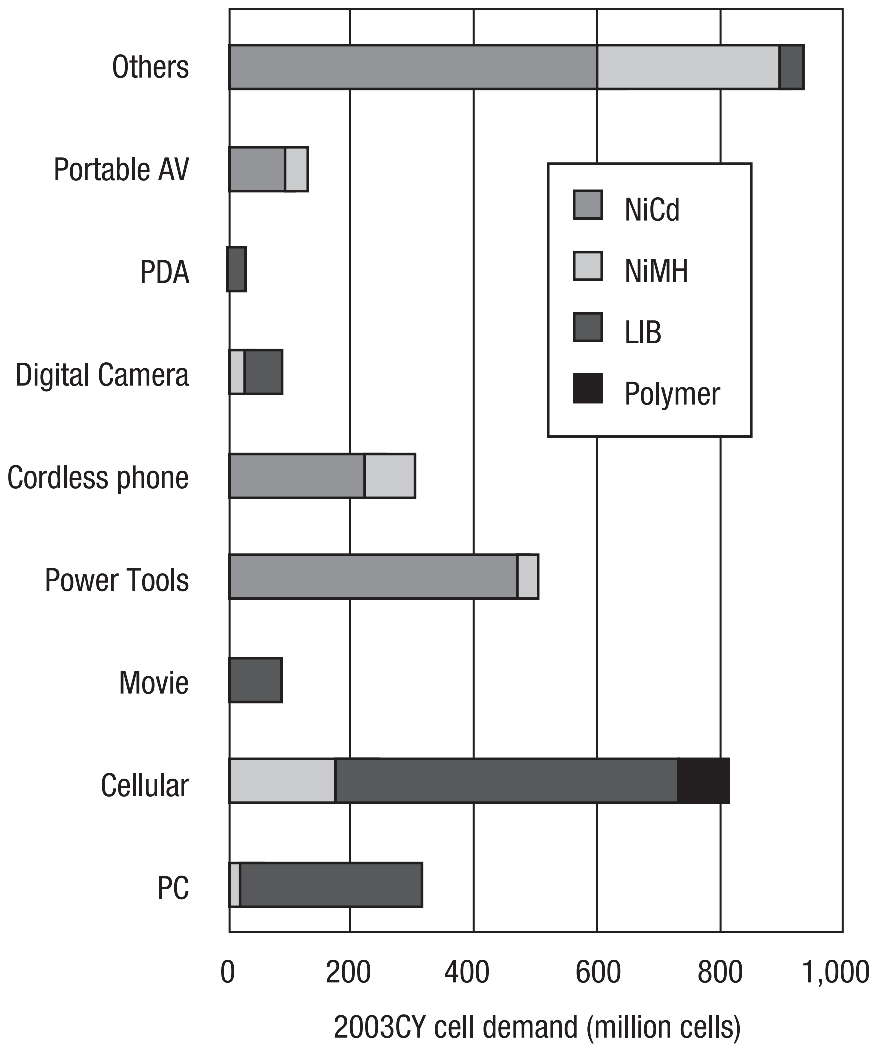
Source: Institute of Information Technology, Ltd. Japan. 2002.

Ni-MH batteries could be produced using the same equipment as that used for Ni-Cd batteries. Prices will soon drop for Li-ion polymer cells, however, following trends that applied for Li-ion cells. Because the chemistry is the same, the energy storage capability is the same for Li-ion polymer and Li-ion technologies. The Li-ion polymer cell uses a soft packaging that is lighter and lower in cost. With time, both Li-ion and Li-ion polymer cells should approach the same selling price, with Li-ion polymer cells having an edge due to lower packaging costs.

Figure A3.3 shows the distribution of the rechargeable markets by each use.

Li-ion battery sales growth stalled in 2001, with global Li-ion battery production growing only 3.7 percent to 560 million units, and falling by 11.1 percent in value to 336 billion yen due to lower prices (as reported by Japan-based market research firm Chunichisha). Unit production did not grow at a double-digit rate due to weak demand from mobile phones, which account for 50 percent of the Li-ion battery use. Note that these data are not consistent with Figure 3.1. This may be because Chunichisha missed the increased production volume in China and South Korea by 2002. In addition, prices fell as low as 500 yen for a 18650 size cell during the second half of 2001, and prices are facing further pressure from low-priced products from China and South Korea and downstream electronics assemblers.

Figure A3.3. Uses for Each type of Battery



Source: Institute of Information Technology, Ltd. Japan. 2002.

Appendix 4. Comparison of Battery Technologies

Batteries are portable sources of stored chemical energy that convert directly into electrical energy at high efficiency on demand. Primary batteries are used once and then thrown away. Secondary, or rechargeable, batteries can be electrically restored to their original chemical state.

Table A4.1 summarizes the recent and expected future worldwide market sizes for these broad classes of batteries. As of 2002, the total market was about $54 billion, with an annual overall growth rate of about 7 percent for primary cells and 8 percent for secondary cells. In the United States (not singled out in the table) 2002 battery market and battery related product market sales totalled $11.4 billion and were forecasted to grow to $15.5 billion by 2007, a projected average annual growth rate of 6.4 percent.

In the secondary, or rechargeable, category several entirely new classes of batteries have been commercialized during the past 15 years, including Ni-MH, Li-ion polymer, Li-ion rechargeable alkaline, and mechanically rechargeable zinc-air designs. The small, sealed battery market segment, not listed separately by Freedonia, includes nickel cadmium (Ni-Cd), Ni-MH, and Li-ion. In Table A4.1, the Li-ion battery system is included in the *Other* category, while its competitors Ni-MH and Ni-Cd are included in the *Nickel* battery category. This segment serves as the energy source for the portable electronic device market and has seen spectacular growth over the past 10 to 12 years.

Table A4.1. Estimated Sales of Batteries, Worldwide ($, Millions) 2002

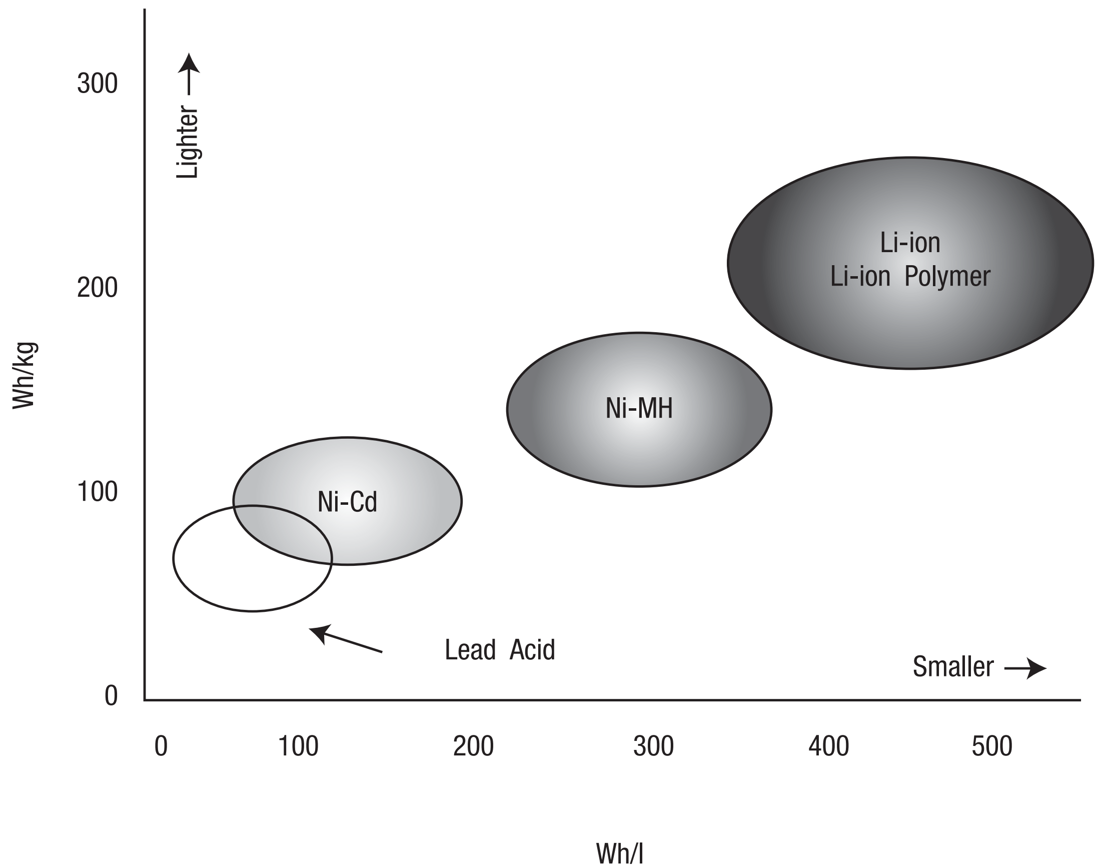
		1997	2002	2007
Primary	Carbon Zinc	6,860	7,415	7,765
	Alkaline	6,170	10,330	16,425
	Other	2,425	4,030	7,765
	Subtotal	15,455	21,775	30,575
Secondary	Lead Acid	13,715	18,805	24,980
	Nickel	5,630	7,825	10,290
	Other	2,720	6,295	11,680
	Subtotal	33,065	32,925	46,950
	Grand Total	48,520	53,700	77,525

Source: The Freedonia Group

Improved microelectronic battery charger controller technology—in particular lithium-ion polymer and lithium-ion—is enabling the commercialization of these new classes of batteries. It is also improving the marketability of existing battery systems, e.g., nickel cadmium and lead acid. In turn, this has accelerated portable computer, cellular telephone, and cordless hand tool product development to a degree that would be impossible without improved power management. Nevertheless, non-rechargeable batteries maintain their established role as the power source for many kinds of portable products.

Figure A4.1 compares the energy storage capability of these new systems. Energy storage is expressed as watt-hours per unit volume (Wh/l) and watt-hours per unit weight (Wh/kg). The larger values of Wh/l translate into a smaller cell, while larger values for Wh/kg translate into lighter weight for a

Figure A4.1. Comparison of Energy Density of Various Small, Sealed Battery Systems



given cell voltage and ampere-hour capacity. The high values of Wh/l and Wh/kg have been key factors in its rapid growth.

In the marketplace, the small, sealed rechargeable battery systems form a unique market segment in the sense that they compete for similar portable applications. Sealed lead acid may also be included in this category. Table A4.2 compares the advantages and disadvantages of the various battery systems along with their principal applications.

The market for portable battery-powered products has grown from a few well-established niches, such as flashlights, portable radio, cassette and CD players, and wristwatches, to a diverse rapidly growing market that encompasses electronic computers, communications and entertainment products, a variety of cordless tools, and whole new classes of military and medical products. This diversity has been accomplished because of the unique synergy between the products themselves, the batteries they employ, and the battery charger and power management systems that charge the batteries.

Table A4.2. Summary of Performance and Applications for Small, Sealed Rechargeable Batteries

Advantages	Disadvantages	Applications
Lithium-ion (Li-ion)		
Highest energy storage (Wh/l)	Relatively expensive	Cellular phones
Light weight	Electronic protection circuitry	Notebook Computers
No memory effect	Thermal runaway concern	Camcorders
Good cycle life	3-hour charge	
High energy efficiency	Not tolerant of overcharge or over discharge	
High unit-cell voltage		
Lithium-ion Polymer (Li-ion Polymer)		
Same chemistry as Li-ion	Lower high rate	Same applications as Li-ion
Lighter weight (Wh/kg)	Plasticized electrolyte	PDAs
Flexible footprint	3-hour charge	
Internal bonding of anode to cathode	More expensive	
Nickel Metal Hydride (Ni-MH)		
Higher capacity than Ni-Cd	Poor charge retention	Low-end electronic devices
Cadmium Free	High cost negative	First production in 1992
Rapid Recharge	Memory effect	Used in HEV
Long cycle life	Lower high rate than Ni-Cd	
	Low unit-cell voltage	
Nickel Cadmium (Ni-Cd)		
Long cycle life	Lower capacity	Power tools
Excellent high rate	Memory effect	Portable phones
Rapid recharge	Environmental concerns	Low-end electronic devices
Good low temperature	Poor charge retention	Standby power
Robust chemistry	Low unit-cell voltage	
Lead Acid		
Inexpensive	Low energy density	Emergency lighting
Sealed value regulated technology	Sulfation on stand	
Good high rate	Intermediate unit-cell voltage	

Table A4.3 summarizes market sizes for small, sealed batteries and the expected near-term trend as of 2000. Li-ion and Li-ion polymer systems, along with Ni-MH and Ni-Cd systems, compete in the market segment for small, sealed, rechargeable batteries. Notebook computers and cellular telephones are the major applications for Li-ion batteries. Other applications include video cameras, digital cameras, and DVD and CD players. These have been high growth applications for almost 10 years. The high-energy, lightweight Li-ion batteries give these devices longer run time and greater portability and have, over the past 10 years, doubled the runtime possible between charges, which has been a critical factor in gaining consumer acceptance of new products. Formerly, the Ni-Cd system dominated this category. Because of its lower energy storage capability, it is no longer a big factor in this segment, although Ni-Cd does find application in low-cost devices and power tools.

Table A4.3. Market Data for Unit Cell Production and Dollar Value for Rechargeable Batteries for 2000 with Estimated Growth to 2003

System	Year	2000	2001	2002	2003
Ni-MH	Millions of Cells	1239	1103	953	880
	Value ($Millions)	1268	1153	915	807
Li-ion	Millions of Cells	530	611	726	824
	Value ($Millions)	2926	2977	3431	3670
Li-ion Polymer	Millions of Cells	15.4	29	51	102
	Value ($Millions)	128	200	316	490
Ni-Cd	Millions of Cells	1295	1295	1205	1110
	Value ($Millions)	1204	843	1005	1078

Source: Institute of Information Technology, Ltd. Japan. 2002.

Appendix 5. Li-ion Batteries: Market Participants

According to Yoshino, Asahi Chemicals in Japan started R&D work on Li-ion batteries in the early 1980s and acquired the first patents on its technology in 1987. Sony published details of its system in 1991. Device manufacturers quickly saw the advantages of longer lasting, lighter weight batteries for their cellular phones and notebook computers. The Li-ion system provided up to four times the run time with one-third the weight of the Ni-Cd system, which was the standard of performance at the time.

These initial Li-ion manufacturers were large electronics companies with active battery R&D and manufacturing. Sony, Matsushita, and Sanyo all had significant R&D programs in the area, and each invested about $150 million in production facilities in quick succession. Starting in 1991, they invested heavily in production capability; this investment continued throughout the decade and, in some cases, amounted to as much as $1 to $2 billion or more. Motorola had a significant R&D effort to develop its own Li-ion polymer technology. After completing the development, rather than pilot and produce the cells themselves, Motorola decided to license the technology as did Telcordia (now SAIC).

Today the principal manufacturers of Li-ion batteries are, with the exception of BYD in China, large, vertically integrated Japanese and Korean producers of consumer electronics. These account for all of the Li-ion batteries produced in Japan, where about 80 percent of the world's production of

Li-ion batteries is located (the rest is in China, Taiwan, and South Korea).

Japanese Li-ion battery production goes first to captive in-house uses for a company's own portable electronic devices. The remaining production (a sizable percentage of the total production) is sold to other original equipment manufacturers (OEMs) of portable devices. These manufacturers have established very high standards for quality, performance, and safety for their products. Device designers will share future product development and designs within their own company but are reluctant to share the same data with outside suppliers.

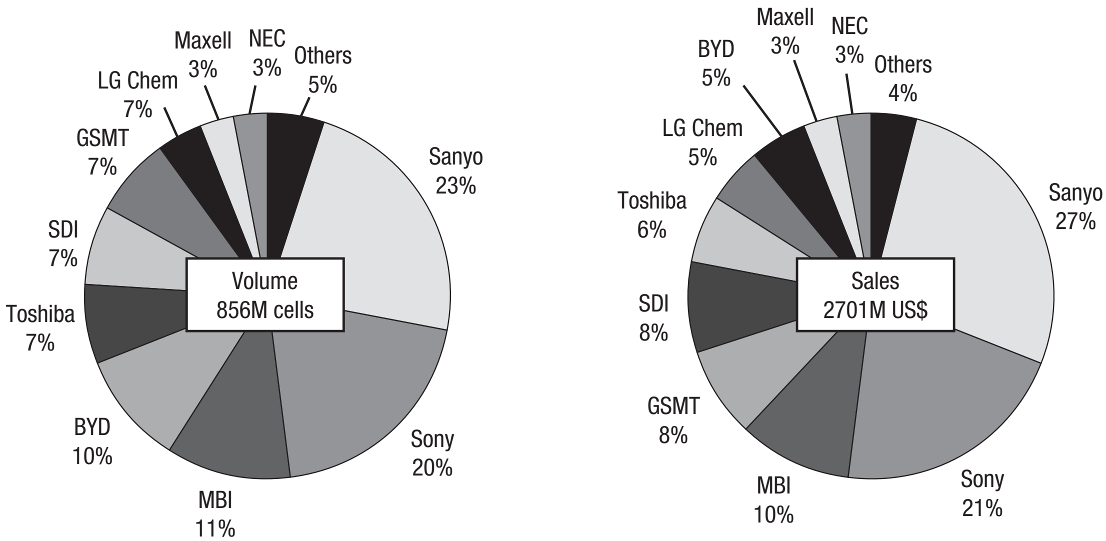
Figure A5.1 summarizes current market shares for Li-ion batteries, as assessed by the Institute of Information Technology, Ltd. Its data show that volume exceeded 800 million cells by 2002, when value reached nearly $3 billion.

Although Ni-MH and Li-ion had been forecast to replace Ni-Cd batteries, it should be noted that Ni-MH and Li-ion systems took the market expansion, while the Ni-Cd systems maintained the low-end electronics and power-tool markets.

In 2003, BYD of China became a significant supplier, as did South Korean companies Samsung and LG Chemical (formerly Lucky-Goldstar). The manufacture of Li-ion batteries has begun to shift from Japan to China as some major producers take advantage of the Chinese government's willingness to provide low-cost loans and production facilities or support for companies that bring strategic new technologies to China. South Korea also provides government incentives and has essentially the same cost structure as China. In the past three years, Samsung and LG Chemicals entered the market. Samsung penetrated the market and captured the fifth spot in production capability, with LG not far behind.

Major Japanese and Korean manufacturers of portable electronic devices have their own integrated Li-ion battery production facilities. They have pursued aggressive research and

Figure A5.1. Li-ion Market Share for 2002



Source: Institute of Information Technology, Ltd. Japan. 2002.

development efforts, leading the way in making engineering improvements as well as developing new materials to enhance Li-ion performance. The governments of South Korea and China have made Li-ion systems a strategic technology. Both governments have encouraged investment in the development of new technology, and support new production facilities with loans or grants.

In preparation for the 2008 Olympics, the Chinese government has designated both Li-ion and fuel cell systems as strategic technologies. This has attracted new production from Japan to China, given the potential size of Chinese markets for portable electronics devices. New production facilities are being constructed in China, some as joint ventures between Chinese companies and major Japanese companies. As a quid pro quo, Chinese participants get government funding to assist in building facilities, and the Japanese partner supplies the technology.

Battery pack assembly operations have been shifting from Mexico to China to take advantage of lower labor costs. This is the most labor-intensive part of battery manufacturing.