

# 6

## Rechargeable Li-ion Batteries\* for Satellite Applications: Pros and Cons

J-M. Tarascon<sup>†</sup> and G. G. Amatucci<sup>‡</sup>

### 6.1 Introduction

For many years rechargeable lithium batteries have been considered a superior alternative power source for a wide variety of applications. However, it is only since the 1990s that rechargeable lithium-ion (Li-ion) cells have become key components of the portable, entertainment, computing, and telecommunications equipment required by an information-rich, mobile society. The electric vehicle (EV) industry, always searching for long-lasting batteries with greater autonomy, is seriously considering the rechargeable Li technology as a viable solution. The aerospace industry is also in need of improved batteries. Satellite reliability, cost-effectiveness, and performance depend on many factors, a critical one being the selection of an appropriate battery technology.

This chapter will discuss the advantages and disadvantages of the Li-ion technology as a powering source for satellite applications. A rechargeable plastic Li-ion battery (PLiON™) technology, a modified version of the liquid Li-ion technology first commercialized in the 1990s by Sony, has recently been developed. Advantages of this technology with respect to satellite and, more specifically, nanosatellite applications will be discussed. Performance and design flexibility of this technology will be compared with those of Ni/Cd or Ni/H<sub>2</sub> batteries, currently used for satellite applications.

A successful satellite mission depends on the proper function of the power system of the spacecraft in orbit over extended periods of time; therefore, continual efforts are being made to realize more reliable power systems. The electrical power onboard a spacecraft generally involves four basic elements:

- A primary source of energy such as a solar cell
- A device for converting the primary energy into electrical energy
- Chemical batteries for storing the electrical energy to meet the peak and/or eclipse demands
- A system for conditioning charging/discharging<sup>†</sup>

The main source of primary power for satellites is solar radiation. However, such a primary source of power, if not coupled with a supplementary source that can store electrical energy, is of little use in most applications. Chemical sources such as rechargeable batteries serve such a purpose. Specifications of a battery for satellite applications depend on the spacecraft power requirements, which are contingent to a large extent upon the nature of the mission.

In any spacecraft power system based on the use of solar energy, the storage battery is the main source of continuous power since it is called upon to respond to peak and eclipse power demands. Such demands depend upon the satellite orbit. For low Earth-orbit (LEO) spacecraft, the number of eclipses increases as the altitude decreases. Typically, for a 550-km orbit, there will be about 15 eclipses per day, 5500 per year, or about 40,000 per usual satellite lifetime (e.g., 7 years). This

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<sup>†</sup>Université de Picardie Jules Verne, Amiens, France

<sup>‡</sup>Bellcore, Energy Storage Research Group, Red Bank, New Jersey

translates into 40,000 charge/discharge cycles for the selected battery.<sup>1</sup> These cycles will not be deep cycles (the percentages will be defined later) since for an orbital radius of 550 km, the duration of each eclipse is estimated to be 36 min. Although partial charge/discharge cycles are required, with such a large number it is mandatory that the power storage system proceeds reversibly without loss (e.g., without any capacity loss between subsequent charge/discharge cycles). An additional factor of importance for satellite applications is the weight, since each additional pound shortens the lifetime of a satellite in orbit by one month and adds to the launch costs associated with the satellite. Therefore, the rechargeable batteries must be lightweight (e.g., batteries with large gravimetric energy densities).

In short, "an ideal storage cell" for space applications has the following primary requirements.

- Ability to accept and deliver power at high rates
- Long charge/discharge cycle life under a wide range of conditions
- High recharge efficiency
- Low impedance
- Good hermetic seals throughout thousands of electrical cycles involving concurrent pressure and thermal changes
- Operation in all physical orientations
- Ability to withstand launch and space environments
- Stable long-term overcharge characteristics
- Maximum usable energy per unit weight and volume at low cost with high and proven reliability

At present no single battery technology can meet all these requirements. Choosing a technology, therefore, depends mainly on a knowledge of the available and emerging rechargeable batteries, which requires a detailed survey of such technologies. Rather than conduct a complete survey of various technologies, we present how an emerging technology, that is, the Li-ion technology both in its liquid and plastic form, can provide a viable solution to the powering issues faced by satellite applications.

The chapter is in three sections. The first introduces battery nomenclature and briefly retraces the historical development of lithium batteries. The second deals with the chemistry, materials issues, and performances of Li-ion technology in conjunction with a comparative study of the performance of the Ni/Cd and Ni/H<sub>2</sub> battery technologies already accepted for use in today's satellites. The final section introduces the plastic Li-ion technology and its potential for space applications through exploitation of its intrinsic design and flexibility. A tentative time is forecast for the implementation of the Li-ion technology either in its liquid or plastic forms with respect to space applications, keeping in mind that the choice of a battery depends on suppliers and availability as well as technical characteristics.

## 6.2 Historical Development of Lithium Batteries

### 6.2.1 A General Introduction to Batteries

Just as a molecule is composed of several atoms, a battery is composed of several electrochemical cells. These cells are connected in series and/or parallel to provide the required voltage and capacity, respectively. Each cell consists of a positive electrode and a negative electrode (both sources of chemical reactions) immersed in an electrolyte medium, a solution containing dissociated salts, which allows ion transfer between the two electrodes. Once these electrodes are externally connected through a resistor, chemical reactions proceed in tandem at both electrodes, thereby liberating electrons and allowing a current to flow through the resistor (to perform work). Thus a cell can simply be viewed as an electrochemical device that stores energy in the chemical

form and converts this chemical energy into electrical form during discharge. Depending upon the nature of the chemical reactions taking place at the electrodes, primary and secondary rechargeable cells will be distinguished.<sup>2</sup>

In a primary cell, the chemical reactions are not reversible, so that once discharged, the cell cannot convert electrical energy back into chemical energy and must be disposed of. In contrast, with secondary cells, the chemical reactions are perfectly reversible so that chemical energy can be transformed several times into electrical energy and vice versa.

The amount of electrical energy that a cell is able to deliver is a function of the cell potential and capacity, both linked directly to the chemistry of the system. The cell potential (cell voltage,  $V_{cell}$ ) is the difference between the potential of the redox reactions occurring at the positive ( $V^+$ ) and negative ( $V^-$ ) electrodes simultaneously.

$$V_{cell} = V^+ - V^- \quad (6.1)$$

The cell capacity refers to the total quantity of electricity (number of electrons transferred) involved in the electrochemical reaction and is defined in ampere-hours ( $Ah$ ). The gravimetric capacity of an electrode in  $Ah/g$  units is defined as the number of electrons involved in the redox reaction multiplied by 26.8  $Ah$  (26.8  $Ah$  being the capacity delivered by 1 gram-equivalent weight of material) and divided by the molecular weight of the active material ( $Ah/g$ ).<sup>3</sup>

$$\text{Capacity} \left( \frac{Ah}{g} \right) = \frac{26.8ne(Ah)}{MW} \left( \frac{Ah}{g} \right) \quad (6.2)$$

The product of the  $Ah$  of an electrode material (or complete cell) and its potential will give its energy density ( $Wh$ ),

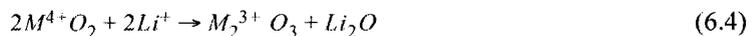
$$\text{Energy density} (Wh) = AhV, \quad (6.3)$$

which can be expressed either per gram (gravimetric  $Wh/kg$ ) or per liter (volumetric  $Wh/l$ ). Both energy density characteristics are critical in evaluating the performance of battery technology.

The power energy of a cell refers to the rate at which the cell can release its chemical energy. We will use the C-rate scale, where 1 C is the current at which the battery energy will be fully utilized in one hour. The capacity delivered at 1 C is compared with theoretical capacity and is given on a percentage scale. For example, percentage capacity can be given for different rates, C/2 for 2 hours and 2 C for half an hour.

### 6.2.2 Why Li Metal?

The motivation for using a battery technology based on Li metal lies in the fact that it is the lightest and also the most electropositive metal in the electromotive series. The low atomic mass of lithium compared with that of lead, for instance, results in a specific capacity of 3800  $Ah/Kg$ , 14 to 15 times higher than that of lead or 4 to 5 times higher than that of nickel (260  $Ah/Kg$  and 900  $Ah/Kg$ , respectively). The advantage of using Li metal was first demonstrated in primary Li cells.<sup>4</sup> Such cells used Li as anode and an inorganic compound as cathode, which when electrochemically reacted with  $Li^+$ , led to an irreversible displacement/decomposition reaction of the general type:



Where  $M$  is a transition metal, this type of reaction is irreversible.<sup>2,4</sup> However, there now exists an entirely different family of inorganic compounds, called intercalation compounds, that are able

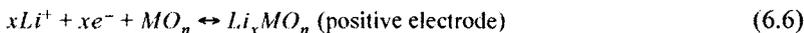
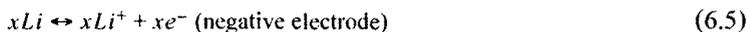
to reversibly intercalate cations ( $A^+ + e^- + MX_n \leftrightarrow AMX_n$ ) while maintaining their framework structure.<sup>5,6</sup> Within an intercalation reaction a guest specie ( $A^+$ ) can reversibly enter and be removed from the vacant structural sites of the host structure ( $MX_n$ ). Intercalation can only occur if the host material has both a crystallographic and electronic structure that is able to accept ions and electrons, respectively. Among the basic requirements for the solid-state intercalation electrode materials are

- Ability to reversibly insert maximum amount of  $Li^+$  (resulting in a large electrochemical capacity)
- High diffusion of the guest species in the host (resulting in high-power densities)
- Minimal structural change (e.g., resulting in highly reversible reaction)
- Good electronic conductivity to eliminate the need for conducting additives
- Low solubility in the electrolyte to prevent high self-discharge
- Large free energy of reaction (high voltage)<sup>2</sup>

The chemical potential of Li into the intercalation material is governed by the redox potential of the transition metal  $M^{+n} / M^{+(n-1)}$  redox reaction, which is a strong function of the ionic-covalent nature of the  $M-X$  ( $X$  is an anion) bond.<sup>7</sup> The highest potential is established by bonds with the greatest ionicity, which is why oxides exhibit greater potential than the more covalently bonded chalcogenides. In addition, the chemical potential is also governed by the local environment of the intercalating Li ion. For example, a lithium ion tetrahedrally coordinated by the oxygen ligands may have a higher voltage than a lithium ion situated in an octahedral coordination.

In the 1970s, researchers recognized the possibility of utilizing intercalation reactions at the cathode of a galvanic cell. A typical rechargeable lithium intercalation battery [Fig. 6.1(a)], proposed in the 1970s on this principle, uses as the positive electrode, an intercalation material;<sup>5,6,8</sup> as the negative electrode, lithium metal; and as the electrolyte, a solution of some Li-bearing salt in an organic electrolyte (for instance  $LiPF_6$  in a mixture of ethylene carbonate and dimethyl carbonate).

During the charge and discharge cycles of a rechargeable Li cell, as indicated by Eqs. (6.5)–(6.7), the positive electrode material undergoes a bulk reversible electrochemical reaction (lithium deintercalation $\leftrightarrow$ intercalation within the open structure of the material).



Surface reactions, namely lithium plating and stripping on the electrode surface, occur at the lithium metal electrode.

Despite numerous intercalation electrode materials, only primary lithium metal cells such as  $Li/CF_x$  and others have been commercialized to date. The difficulties in commercializing room-temperature rechargeable Li metal batteries, despite their promises in laboratory prototypes, can largely be traced to safety problems associated with the use of lithium metal as the anode. During subsequent charge/discharge cycles, Li is removed and replated on the metallic Li negative electrode. Dendrites or low-density, highly reactive, “mossy” lithium may be formed instead of smooth replating on the Li metal surface. The dendritic growth of lithium during the recharge cycle can lead to electrical shorts through the separator and catastrophic failure of the battery.<sup>9</sup>

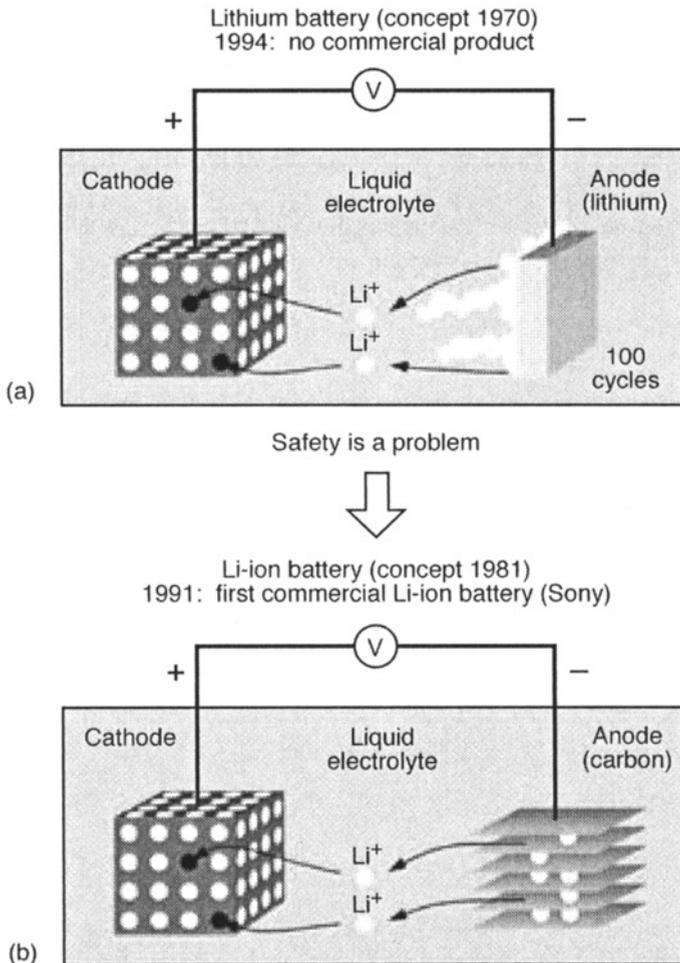


Fig. 6.1. (a) Graphical representation of the  $\text{LiMn}_2\text{O}_4$ /liquid electrolyte/Li-metal battery showing formation of deleterious Li metal dendritic growth on the anode. (b) Representation of the Li-ion battery technology in which the Li metal anode is substituted for a carbon-based intercalation compound.

### 6.3 The Li-ion Battery

In the early 1980s, two approaches were proposed to circumvent the problems associated with the growth of lithium dendrites at the negative electrode. One approach replaces the liquid electrolyte with a solid polymer electrolyte, which impedes the growth of dendrites between the two electrodes.<sup>10</sup> This research led to the so-called lithium solid polymer batteries, extensively studied, by Hydroquebec of Canada for example, during the last 20 years.<sup>11</sup> While this approach is compatible with large-scale manufacturing techniques, it has not completely solved the dendrite growth problem. The other approach replaces the metallic lithium at the negative electrode by another intercalation compound (e.g., another lithium sponge) so that the lithium activity is reduced, since no lithium metal exists in this battery, only lithium ions.<sup>12–14</sup> A battery fabricated this way, in which the lithium ions can be shuttled (or rocked) from one sponge to another as the cell is cycled, is commonly known as a Li-ion or “rocking chair” battery [Fig. 6.1(b)]. When optimized,

these batteries have lower energy densities than the Li-metal batteries; however, they exceed existing battery technologies in both gravimetric and volumetric energy densities (Fig. 6.2).

The Li-ion battery is typically fabricated in its discharged state, with the lithium contained as ions within structural sites of the cathode material. In Li-ion technology, no lithium metal exists. The schematic in Fig. 6.3 illustrates the reactions involved during the charging and discharging of the cell.<sup>16</sup> During the charge cycle of the Li-ion battery, Li-ions are extracted (deintercalated) from the cathode structure and passed into the ionically conductive electrolyte. Simultaneously, an electron is extracted from the transition metal in the cathode and is passed through the external circuit. The result is oxidation of the transition metal. The lithium ion is then intercalated (instead of plating on Li metal) into the anode intercalation material from the electrolyte simultaneously with the electron from the external circuit.

During the discharge cycle, the reverse reaction takes place. The electron is removed from the anode and is passed through the external circuit where the subsequent electric current is used to do work. It then reinserts into the cathode by charge transfer and reduces the transition metal. Simultaneously, the lithium ion is extracted from the anode, passes through the electrolyte, and re-intercalates into the cathode. The output voltage of the cell is simply the difference in chemical potentials versus  $\text{Li}/\text{Li}^+$  of the cathode and anode.

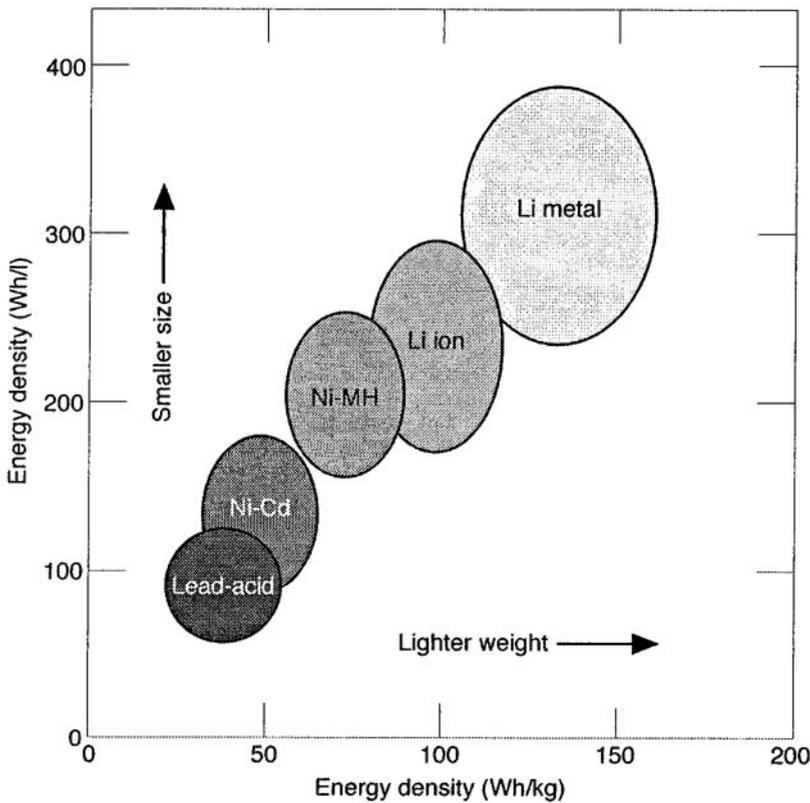


Fig. 6.2. Comparison of volumetric and gravimetric energy densities for a variety of rechargeable battery systems.<sup>15</sup>

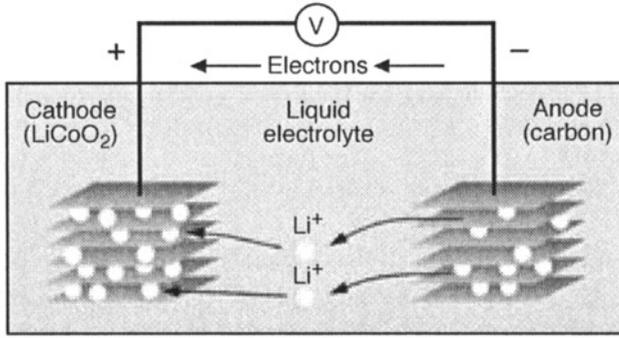
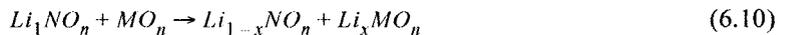
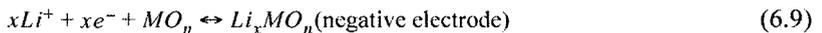
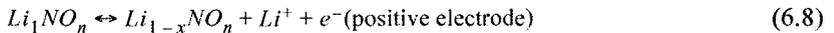


Fig. 6.3. Illustration of the electrochemical reactions that occur in the Li-ion battery upon charge and discharge.

This type of battery is inherently safer because in contrast to the metallic state where Li is reduced in Li-metal batteries, in the Li-ion battery, lithium is always confined to the ionic state. Sony was the first company to commercialize a Li-ion cell in June 1991,<sup>17</sup> and several other battery companies (Sanyo, Matsushita, Fuji, Toshiba, Hitachi, Yuasa, Moli<sup>18</sup>) are currently developing the Li-ion technology using a liquid organic electrolyte. The feasibility of large-size Li-ion batteries for EV applications was demonstrated in 1996 by Sony. This demonstration of the Li-ion technology scalability opens new markets for the Li-ion battery, namely, the space application market where Li-ion technology could favorably compete with the Ni-Cd and Ni-H<sub>2</sub> technologies that dominate this application domain.

### 6.3.1 The Chemistry

To alleviate the safety problems associated with a lithium-metal based battery, a Li-ion cell utilizes intercalation reactions at the cathode and at the anode, as indicated in Eqs. (6.8)–(6.10). However, a price is paid in terms of average output voltage and energy density as compared to a lithium metal cell. In addition, replacing Li metal by another intercalation compound results in an overall cell capacity penalty, which can be minimized by selecting intercalation anodes having large electrochemical capacities. The following reaction equations show intercalation reactions for positive and negative electrodes using transition metal (M, N) oxides as intercalation hosts for both the positive and negative electrodes.



A Li-ion cell's voltage is defined by the difference in the chemical potential of lithium within each intercalation electrode material; therefore, to ensure a high cell voltage and high energy density, strongly oxidizing (e.g., high  $V^+$ ) and strongly reducing (e.g., low  $V^-$ ) intercalation compounds must be used for the positive and negative electrodes, respectively. A  $V^-$  that is too close to 0 V is not totally satisfactory either, since it will enhance the risk of the Li plating at the negative electrode during the recharge of the Li-ion cell, thereby defeating the purpose of the Li-ion concept.<sup>19</sup> Because of this danger, compounds with intercalation voltages slightly above that of 0 V versus  $Li/Li^+$  are used. Present day compounds are now approximately 0.01–0.05 V versus

Li/Li<sup>+</sup>. Furthermore, while very attractive, the use of both highly oxidizing and reducing intercalation electrodes also necessitates electrochemically stable electrolytes that can operate over a wide range of potential (0–5 V).

Within a Li-ion cell, the positive electrode stands as the only source of Li, so for practical manufacturing, this electrode must be stable in air. In light of this, only lithiated compounds for which the chemical potential of Li is greater than 3.4 V (greater than the oxidation potential of water vs Li) present a potential interest for Li-ion batteries. If Li potential is lower than 3.2 V, then this compound will be oxidized by water ( $Li_xMO_n \rightarrow MO_n + LiOH + H_2$ ).

In short, implementing the Li-ion concept requires high-performance electrode and electrolyte materials. This is the reason why Li-ion technology took many years to reach the marketplace. The first functioning rocking-chair batteries were based on lithiated negative electrode materials. Systems using LiWO<sub>2</sub>,<sup>20,21</sup> Li<sub>6</sub>Fe<sub>2</sub>O<sub>3</sub>,<sup>22</sup> or Li<sub>9</sub>Mo<sub>6</sub>Se<sub>6</sub><sup>23</sup> as the negative electrode combined with TiS<sub>2</sub>, NbS<sub>2</sub>, or Mo<sub>6</sub>Se<sub>6</sub> as the positive electrode were built and tested.<sup>24</sup> Because of the low V<sup>+</sup> and high V<sup>-</sup> output voltages of these materials, the specific energy density for such Li-ion cells was at least 3 times lower than that for their Li-metal counterparts and even lower than that of Ni-Cd cells. In addition, the negative materials were not air stable. To improve some of these drawbacks, rocking-chair cells based on new lithiated positive electrode materials were proposed in which the air-stable layered intercalation compound LiCoO<sub>2</sub> was coupled with either MoO<sub>2</sub>,<sup>25</sup> WO<sub>2</sub>,<sup>25</sup> or TiS<sub>2</sub><sup>26</sup> negative electrodes. The highest Li intercalation voltage of 4 V for the LiCoO<sub>2</sub> positive electrode material allowed the use of TiS<sub>2</sub> (previously given in example as a positive electrode) as a negative electrode in the cobalt system. The TiS<sub>2</sub>-based cell was found to have the largest capacity, but because of the low output cell voltage (due to the remaining large V<sup>-</sup>), its energy was well below that of the Li-metal counterpart cell or just similar to that of the Ni-Cd cells. The poor performance of the Li-ion systems alluded to above combined with the costly synthesis of the initial negative electrode materials from the non-lithiated material did not justify their commercialization.

These studies confirmed the viability of the Li-ion technology, but also showed that the practical benefits of this technology were limited by the lack of high-capacity negative electrode materials. The discovery by Japanese researchers<sup>27,28</sup> that some forms of carbon (C) could be used as reversible low-voltage lithium intercalation materials drastically changed the scenario. Following this discovery, a carbon (V<sup>-</sup>) / LiCoO<sub>2</sub> (V<sup>+</sup>) rocking-chair cell with a performance exceeding that of Ni-Cd cells was demonstrated. Recent developments in the field of rechargeable cells utilizing carbon anodes as the negative intercalation compound have resulted in batteries with specific energies almost twice that of Ni-Cd batteries.<sup>22</sup> Moreover, the carbon materials used as negative electrodes have the important advantage of being abundant, inexpensive, and nontoxic. They exhibit a highly reversible electrochemical behavior, thus fulfilling the three important requirements for a technology to succeed: safety, performance, and affordable cost.

## 6.3.2 Li-ion Battery Technology: Materials Issues

### 6.3.2.1 Positive Electrode

Over the years, numerous materials have been evaluated for their potential use as intercalation electrodes. Figure 6.4 shows the voltage range for lithium intercalation in various known lithium intercalating materials. The data clearly show which materials are appropriate to build a high-

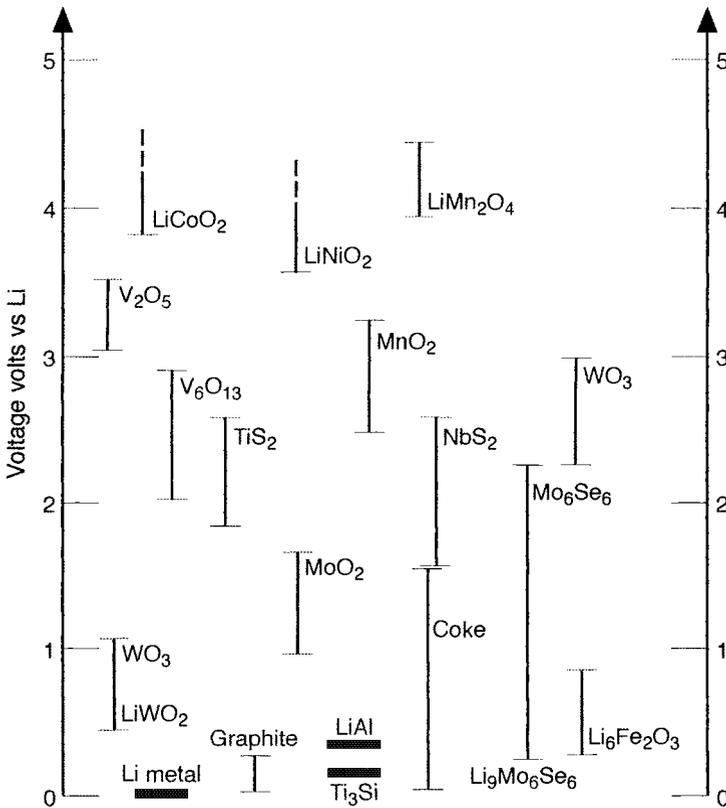


Fig. 6.4. Schematic showing the voltages vs Li for a variety of potential positive and negative electrode materials.

voltage, rocking-chair lithium battery. Materials for the positive or negative electrode should be chosen in the high or low potential range, respectively. Besides  $\text{LiCoO}_2$ , other oxides such as  $\text{LiNiO}_2$ <sup>18</sup> and  $\text{LiMn}_2\text{O}_4$ <sup>29-35</sup> were proposed for use in carbon-based Li-ion systems as they all retain voltages versus  $\text{Li}/\text{Li}^+$  in the 4 V range.  $\text{LiMO}_2$  ( $M = \text{Ni}, \text{Co}$ ) compounds, which can cycle about 0.5  $\text{Li}^+$  ion per transition metal atom, and  $\text{LiMn}_2\text{O}_4$  materials result in carbon-based rechargeable cells performing near the theoretical limit. The  $\text{LiM}^{3+}\text{O}_2$  ( $M = \text{Co}$  and/or  $\text{Ni}$ ) are compounds composed of  $\text{MO}_6$  metal oxide octahedra connected at the edges to form single-layer  $\text{MO}_2$  sheets (Fig. 6.5). Layers of these sheets are separated by interlayer sheets containing Li-ions octahedrally coordinated by oxygen anions contained in the  $\text{MO}_2$  sheets. This results in two-dimensional (2D) pathways, which allow fast lithium-ion diffusion into and out of the structure. In addition, these materials have good electronic conduction, allowing electron charge transfer to the transition metal cations ( $\text{Co}$  or  $\text{Ni}$ ). Upon Li intercalation and electron charge transfer from the external circuit, the tetravalent transition metal cations,  $\text{M}^{4+}\text{O}_2$ , are reduced to trivalent cations,  $\text{LiM}^{3+}\text{O}_2$ .

The  $\text{LiMn}_2\text{O}_4$  structure differs from the layered  $\text{LiMO}_2$  structure in that it contains  $\text{MnO}_6$  octahedra connected to form a three-dimensional (3D) network (Fig. 6.6). This network creates 3D pathways from which Li-ions can be reversibly removed, but the gravimetric and volumetric energy densities are lower for  $\text{LiMn}_2\text{O}_4$ . However, Li-ion cells consisting of  $\text{LiMn}_2\text{O}_4$  electrodes

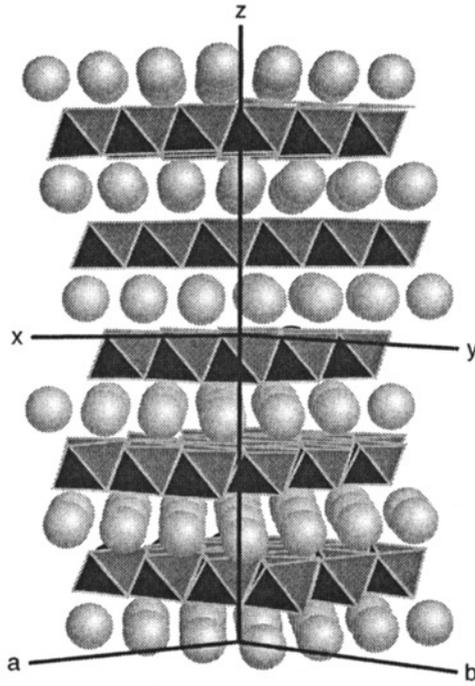


Fig. 6.5. The layered structure of  $\text{LiMO}_2$  (M = Ni and/or Co) showing the 2D pathways for Li diffusion. Balls represent  $\text{Li}^+$ .

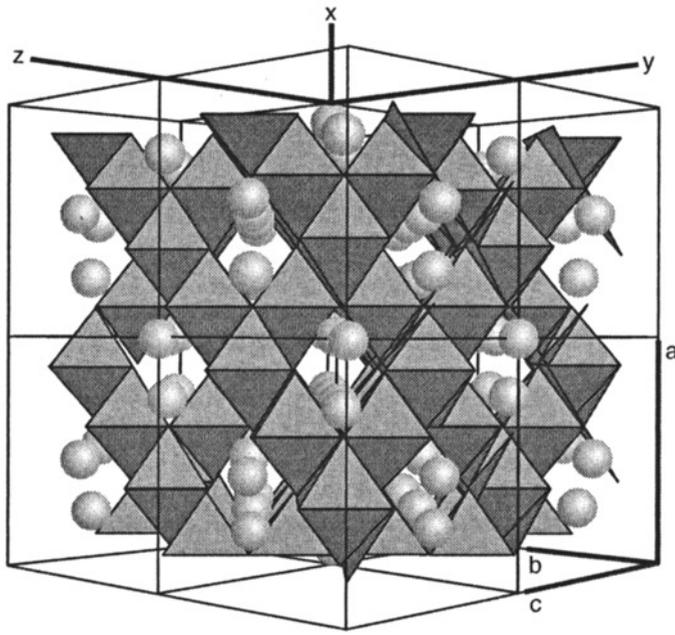


Fig. 6.6. The 3D spinel structure of the  $\text{LiMn}_2\text{O}_4$  positive electrode material showing the 3D pathways for Li diffusion. Balls represent  $\text{Li}^+$ .

offer several advantages over the Li-ion cells based on Ni or Co. These include a lower electrode cost resulting from natural abundance and a lower cost for Mn in comparison with Co or Ni; considerably less-toxic manganese-based oxide materials, which have well-established recycling methods; and improved safety in the charged state offered by the 3D framework structure. The layered structures have a greater tendency to release oxygen under extreme-abuse conditions where internal temperatures approach 200°C.<sup>36</sup> Normally, oxygen is bonded tightly by the transition metals (M) in edge-shared MO<sub>6</sub> octrahedra, which form MO<sub>2</sub> layers. These MO<sub>2</sub> layers are stabilized by interlayer occupation of Li-ions. When the battery is charged and the Li-ions are removed, these layers can become unstable at extreme-abuse conditions (>200°C). When this happens, transition metals move into the interlayer space, resulting in a structural decomposition concurrent with the release of oxygen. The evolved oxygen in combination with the organic electrolyte creates a potential combustion hazard. The 3D framework structure of the LiMn<sub>2</sub>O<sub>4</sub> spinel offers greater resistance to this evolution. Thus, based on its economy, safety, and environmental acceptability, this system is desirable for manufacturing. Although this material appeals to battery manufacturers, they are still hesitant in implementing it in commercial cells because of solubility issues with today's electrolytes.

### 6.3.2.2 Negative Electrode

The most popular negative electrode materials are based on carbon materials. Two major forms of carbon, coke and graphite, have been used in Li-ion batteries. Coke results from annealing carbon in inert atmospheres to temperatures of 1000°C. Graphite is formed after annealing carbons to temperatures approximately 2800°C. Graphite is a hexagonal, layered structure that allows 2D intercalation pathways of Li-ions much like that of the LiMO<sub>2</sub> positive electrodes. The output voltage (V<sup>-</sup>) of graphite negative electrodes are satisfactory; however, improvement in capacity has been the main focus of latest research efforts. Recently, attempts to increase the capacity of the negative electrode have focused in two areas: (1) enhancing the electrochemical characteristics of the carbonaceous negative electrode and (2) finding alternative materials as a substitute for the carbonaceous negative electrode. Chemical or physical means have been used to improve the reversible capacity of the carbonaceous materials. For instance, several enhanced capacity electrode materials have been obtained either by means of a pyrolytic processing of organic materials<sup>37</sup> or by mechanical processing<sup>38</sup> (e.g., mechanical grinding) of the negative electrode material. These approaches, however, have a tendency to produce carbonaceous materials with large irreversible losses and low packing density, so that no significant improvements result when implemented in Li-ion cells. Yoshio<sup>39</sup> has recently reported that some lithiated vanadium oxide-based electrodes, when discharged to voltages lower than about 0.1 V, could reversibly intercalate Li-ions in amounts up to 7 lithium per transition metal so that capacities 2 to 3 times greater than those of graphites could be obtained. However the capacity retention is poor. This was later confirmed by Sigala *et al.*<sup>40</sup> In substituting oxides for graphites as the negative electrode in rechargeable Li-ion batteries, however, a price is paid in terms of cell output voltage since the average voltage at which these V-based oxides intercalate lithium is of 1.4 V compared with 0.3 V for graphite. The energy density of the Li-ion cell based on an oxide rather than graphite is the same within 5%.

### 6.3.2.3 The Electrolyte

An ideal nonaqueous electrolyte for a Li-ion cell should have the same requirements as for rechargeable Li metal cells:

- Low cost
- High ionic conductivity both at room temperature and at -20°C

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- Chemically stable over a wide temperature range ( $-30$  to  $100^{\circ}\text{C}$ )
- Demonstrated electrochemical stability over a wide range potential ( $0$ – $5$  V)

Recent electrolytes,<sup>41</sup> consisting of Li-PF<sub>6</sub> salts and a combination of solvents—e.g., ethylene carbonate (EC) with dimethyl carbonate (DMC)—satisfy most of the required conditions except low-temperature performance. However, adding a third solvent, such as propylene carbonate (PC) for example, allows these cells to function properly down to  $-20^{\circ}\text{C}$ . The main drawback of today's electrolytes is their cost, which to a certain extent dictates the price of the Li-ion technology. The high price is a result of the stringent processing conditions to ensure that the salt and solvent are as dry as possible, since moisture contaminants will result in the formation of hydrogen fluoride (HF). HF has been shown to be detrimental to the performance of Li-ion batteries when present in the system in excess.

### 6.3.3 The Li-ion Battery: Assembly and Function

Like Ni-Cd batteries, Li-ion batteries are assembled in their discharged state and must be charged before use. Discharged Li-ion cells have a potential near zero, which greatly simplifies manufacturing and eliminates the possibility of accidental short-circuiting during assembly. For a Li-ion battery to function properly and efficiently, the mass of the positive and negative electrodes must be adjusted so that they have the same capacity. Cell imbalance may result in either Li plating or electrolyte decomposition. Balancing a Li-ion cell is complicated by the fact that each intercalation electrode exhibits differing amounts of irreversible capacity between the first discharge and first charge, and have different capacity fade rates as a function of cycle number and temperature.<sup>19</sup>

Performances of Li-ion batteries compared with other rechargeable technologies are shown in Table 6.1. These batteries possess higher specific energies and energy densities than Ni/Cd and Ni/MeH cells, and exhibit good rate capability and a long cycle life.

### 6.3.4 Space Allocation Powering Issues: Present Status

The Ni-Cd battery, well known for its high-power-rate capability and long-cycle life, was among the first technologies to be successfully used for space application purposes. More than 27,000 room-temperature cycles at a depth of discharge of about 25% have been achieved.<sup>42</sup> The system consists of nickel oxyhydroxide as the positive electrode; cadmium, the negative electrode; and potassium hydroxide, the electrolyte.

The output voltage of the cell is 1.3 V. Again, these cells are assembled in their discharged state and must be charged prior to their initial use. However, there are concerns with Ni-Cd cells:

- A weight penalty resulting in low specific energy (40 to 58 Wh/kg)
- Dendritic growth of the Cd at the negative electrode that can induce shorts
- Hydrolysis and degradation of the nylon membranes used to separate the electrodes in the battery that can lead to a serious decrease in the cell's lifetime
- Toxicity of Cd

Such concerns have prompted the study, design, and development of more efficient cells. These studies have led to improved Ni-Cd cells (cells that utilize a polypropylene rather than a nylon separator) but more importantly to the development and optimization of the Ni/H<sub>2</sub> batteries that are used aboard GEO and LEO satellites (Hubble space telescope).

Such Ni/H<sub>2</sub> cells<sup>43</sup> are similar to the Ni-Cd cell only in that they still contain the same positive electrode, the negative electrode being hydrogen gas. This technology is superior to the Ni-Cd in terms of energy density (50–80 Wh/kg) and cycle-life (for instance, 4000 cycles with a 75% depth of discharge compared with 800 for the Ni-Cd). Recently, an outstanding performance of 40,000

Table 6.1. Performance Comparison of a Variety of Rechargeable Battery Technologies

Quantity	Ni-Cd	Ni-MeH	LiCoO <sub>2</sub> /C Li-ion (liquid)	Bellcore Liquid Li-ion	Bellcore Plastic Li-ion	Lead-acid
Average voltage (V)	1.2	1.2	3.6	3.8	3.8	2.0
Energy (Wh/kg)	58	70	90–130	100	100–140	30
Capacity (Ah/kg)	48	58	25–36	27	26–37	15
Cycle life	1000+	500	1000	1000	1000	200
Average cost (\$/Wh)	0.88	1.50	2.00	1.20 <sup>a</sup>	0.50 <sup>a</sup>	0.30
Operating temperature range	varies within –20 and 50°C	varies within –20 and 40°C	–20⇔60°C	–20⇔60°C	–20⇔60°C	varies within –20 and 50°C
Toxicity	yes	yes	yes	no	no	yes
Memory effect	yes	varies with processing	no	no	no	no

<sup>a</sup> Estimate based on material costs.

cycles with 40% depth of discharge was reported for Ni/H<sub>2</sub> batteries.<sup>44</sup> Finally, the Ni/H<sub>2</sub> technology is self-protected against accidental overcharge or overdischarge. The oxygen produced during overcharge at the positive electrode reacts with the hydrogen to give water. With this process, the Ni/H<sub>2</sub> batteries can tolerate extended overcharges 4 to 5 times greater than for the Ni-Cd technology.<sup>45</sup> In addition, Ni/H<sub>2</sub> cells exhibit outstanding overdischarge protection.

These cells are preloaded in hydrogen (e.g., there is always a net hydrogen pressure even in the discharged state). During overdischarge the following scenario occurs.<sup>46</sup> After the electrochemically active NiOOH positive electrode is completely reduced to Ni(OH)<sub>2</sub> (e.g., cell completely discharged), water is reduced on this electrode, resulting in hydrogen. This hydrogen is then reoxidized to give water at the negative electrode. The overall result is that during overdischarge the pressure and the water content within the cell remain constant, since once water is reduced at the positive electrode, water is recombined at the negative electrode. On the contrary, in Ni-Cd technology, an overdischarge (e.g., cell reversal) will lead to a significant internal cell pressure. Finally, another important advantage of the Ni/H<sub>2</sub> technology over the Ni-Cd technology is that the hydrogen pressure can be used as an indicator of the state of charge of these batteries. Consequently, the present Ni/H<sub>2</sub> technology, although significantly more expensive than the Ni-Cd technology, offers a greater transparency to harsh operating conditions. This is why the lifetime of Ni/H<sub>2</sub> batteries can exceed 5 years under extreme conditions.

The Ni/H<sub>2</sub> technology is, however, not the ultimate solution to space applications because of a major drawback of extremely high self-discharge. Indeed, a Ni/H<sub>2</sub> battery can lose as much as 50% of its initial capacity at 20°C in only 10 days. The direct interaction of hydrogen with the fully oxidized positive electrode material is at the origin of such a high self-discharge, and it has

been demonstrated that the self-discharge rate varies linearly with the hydrogen pressure (e.g., the more charged the Ni/H<sub>2</sub> cell, the larger the self-discharge).<sup>47</sup> A possible solution to this issue is to lower the hydrogen pressure within the cell (e.g., increasing the cell volume); however, since this can only be done at the expense of lowering the volumetric energy density, such a solution was not pursued.

Another tentative solution regarding this hydrogen pressure has led to the recently emerging low-pressure Ni-MeH technology that is supplanting the Ni-Cd technology for portable consumer applications.<sup>48</sup> Such cells are similar to the Ni-Cd cell, the main difference being that the cadmium electrode has been replaced with a “hydrogen electrode” in which the hydrogen is stored as a medium-cost metal-hydride. Current hydrogen storage materials (i.e., hydrogen “sponges”) such as LaNi<sub>5</sub> can have hydrogen densities greater than that of liquid hydrogen. Ni-MeH cells have up to twice the capacity of Ni-Cd batteries, and significantly higher energy density per unit of volume. However, while these cells show less self-discharge than the Ni/H<sub>2</sub> ones and greater than the Ni-Cd ones (consistent with the kinetics of self-discharge being linked to hydrogen pressure), they exhibit limited cycle-life performance owing to the lack of alloys that exhibit perfect stability against corrosion in KOH media used in the electrolyte solution. Improved hydrogen-absorbing alloys with anticorrosion characteristics must be developed, either through new chemistry or new processing and manufacturing methods in order to improve the cycle life of the Ni-MeH technology before they can be seriously considered for space applications.

Although current Li-ion technology offers significant advantages in performance over the nickel-hydrogen technologies discussed above, there are intrinsic differences between the two technologies, which if not properly accounted for, can result in cell degradation. All nickel-hydrogen technologies make use of an aqueous-based electrolyte. In abuse conditions (overcharge, high-temperature storage, etc.), electrolyte breakdown (water decomposition) will occur, leading to high rates of self-discharge. Recombination reactions, however, make the electrolyte breakdown reversible, and performance can be largely recovered. This is not the case in Li-ion technology. Because of the large range of voltages used in Li-ion, lithium salts dissolved in non-aqueous organic solvents must be used. Under abuse conditions like those discussed in the nickel-hydrogen aqueous technologies, the non-aqueous electrolyte will also undergo decomposition, although to a much smaller degree. Unlike the aqueous technologies, no recombination mechanism exists, and all electrolyte breakdown is irreversible; therefore, although the Li-ion technology has performance advantages, care must be taken not to subject cells to long-term abuse. In light of this, care must be taken to keep long-term operation and storage temperatures as close to 20°C as possible in order to retain extended lifetimes on the order of 10 years. Such cells can operate well in the temperature region near 60°C for shorter times as commonly required by consumer electronics manufacturers. The 20°C temperature range has not been very difficult to maintain in traditional satellite design, but may pose greater difficulty in nanosatellite designs relying solely on passive thermal management schemes.

Attention must also be given to the implementation of good monitoring and charge controls, especially critical in Li-ion technologies using the layered positive electrode compounds of LiCoO<sub>2</sub> and LiNiO<sub>2</sub>. In normal operation, approximately 0.5 Li is reversibly removed from these electrode compounds. If the cells are charged in excess (removing greater quantities of Li), this will have a deleterious effect on capacity retention. In addition, balance between the positive and negative electrode capacities will be altered. The excess Li will have no sites available for intercalation in the negative electrode and will plate, causing the formation of Li metal, which will cause a reduction of cell performance and safety. For the LiMn<sub>2</sub>O<sub>4</sub> positive electrode, all the Li is always removed, so those dangers listed above for the layered compound are not as extreme.

However, even in the  $\text{LiMn}_2\text{O}_4$  case, overcharge for extended periods will cause irreversible electrolyte oxidation and must be controlled. In light of these special considerations, considerable effort has already been expended to make reliable, low-cost monitoring and charge control electronics. This is particularly important when charging groups of cells are placed in series.

In commercial Li-ion batteries, many electronic monitors and controls of the charge/discharge cycles are built into the multicell battery pack. Most circuits include both electronic charge and discharge protection. Placing individual cells in series increases the difficulties with charge control. Although Li-ion battery cells are not charged individually, constant monitoring of each series element is incorporated to set the charge and discharge conditions relative to the weakest cell. This type of control eliminates undue stress on the remaining cells.

Determining the state of charge is an important factor in evaluating completion of the charge and discharge cycles and the overall health of the battery. Such determinations can be evaluated by monitoring both current and voltage. Current is usually monitored and integrated to calculate the coulombs of charge remaining in the battery, generally accomplished through the use of a low-resistance ( $0.05 \Omega$ ) sense resistor. Depending on the active electrodes used in their manufacture, Li-ion batteries can be designed to have either a sloping or a relatively flat discharge profile. At present, this is largely determined by the choice of negative electrode material (Fig. 6.7). For example, the use of graphite as a negative electrode gives a very flat discharge profile, where the voltage changes very little as the cell capacity is consumed during discharge. The flat discharge profile offers an advantage in overall higher energy density of the battery (retains consistently high  $V_{\text{cell}}$ ) and allows a relatively constant current during the full discharge of the Li-ion cell when powering devices that work on a constant power basis. In the graphite case, the current does not have to increase to offset the loss in voltage that would be experienced in the sloping discharge profile for coke to retain a constant power output. However, the flat discharge profile makes charge status determination on the basis of voltage difficult. In the use of coke or “hard-carbon”-

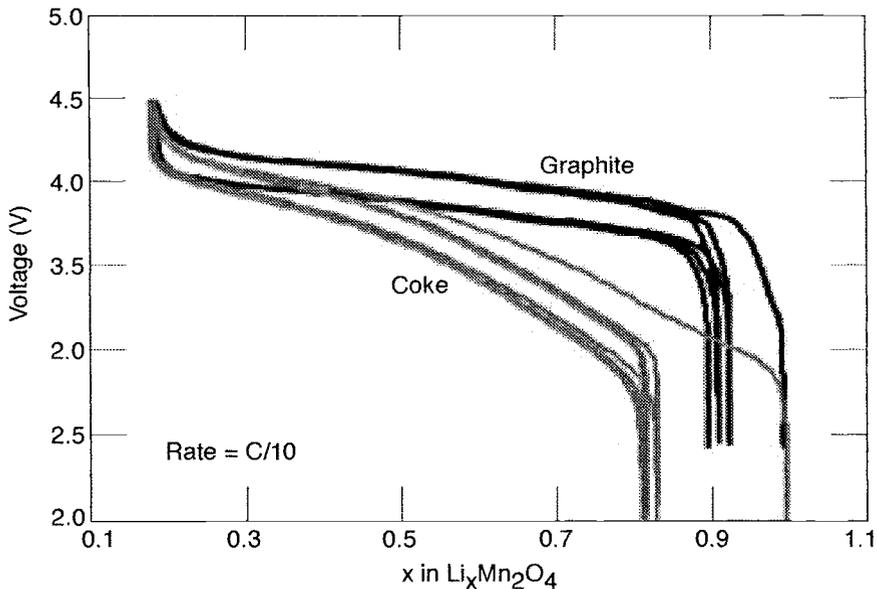


Fig. 6.7. Difference in voltage profiles vs Li content for graphite and coke-based carbon anodes in  $\text{LiMn}_2\text{O}_4$  based Li-ion cells.

based anodes (such as Sony's), voltage profiles slope steeply, and it is much easier to make a determination of the charge status on a voltage basis alone.

In summary, the emerging rechargeable Li-ion technology by no means meets all requirements for powering a satellite, but seems to be the one, when compared with Ni/Cd, Ni-MeH and Ni/H<sub>2</sub>, closest to the "wish list" for space applications outlined at the beginning of this chapter. The suitability of the Li-ion technology for nanosatellite applications is being explored by AeroAstro Corporation. AeroAstro originally developed the Bitsy nanosatellite for the U.S. Air Force and is now making it available for commercial applications. Bitsy is a fast turnaround satellite that can be designed and ready for flight within a few months from order, to be used in areas such as remote sensing, communications, space science, and astrophysics. The satellite is highly integrated and utilizes a single circuit-board design. It is in a very small 1-kg package of 15 × 15 × 5 cm. Thermal control is completely passive, although the option to incorporate active control may be provided. The powering system is based on an 8-V power bus. It is the first nanosatellite designed to use liquid Li-ion cells. These cells will offer 4 Wh of energy.

### 6.3.5 Projections for Future Development

Batteries with greater capacity for increasing mobility during use are in constant demand by consumers. Such demand has generated, and will continue to generate, much research toward the development of new materials. The satellite community will undoubtedly benefit from these efforts. Capacity improvements within a battery technology can result from improvement either in the chemistry of the system (e.g. better materials) or in its engineering (e.g., electrode forming and packing). Usually, engineering improvements are incremental for mature technologies such as Ni/Cd; whereas, material improvements can be drastic for emerging battery technologies. This is especially true for the Li-ion technology that incorporates materials for which only 50% of the total capacity is realized. With the surge of activities toward searching for better electrode materials, the discovery of a cathode that could intercalate/deintercalate one Li per transition metal (Mn, Co, Ni, etc.) must happen. Several directions are being pursued. Among them, one reported by Goodenough,<sup>49</sup> consists of adjusting the ionic/covalent character of the M-X bond by replacing the anion with a polyanion. These materials can now exchange one Li per transition metal at a potential lower than 4 V. However, volumetric capacity (capacity with respect to volume) improvements are less than the gravimetric (with respect to weight), and the diffusion being so slow, such materials cannot at this time be conceived for energy-hungry applications.

For the negative electrode, a common goal is to find materials with a slightly greater intercalation voltage (to completely eliminate the risks of Li plating) and a larger electroactive capacity than present-day carbons. Fuji recently disclosed the fruits of their long research effort employing metal-oxide: the discovery of a negative electrode based on Sn-Si-O, which has an intercalation voltage of about 0.5 V and a capacity twice that of carbon.<sup>50,51</sup> Li-ion cells with 50% improvement in the overall cell capacity were claimed by Fuji, which announced the production of such a new Li-ion cell by the end of 1998.

Li-ion technology, while the most attractive, is still in its infancy, and major breakthroughs in materials have yet to come. It is left to the creativity and innovation of the solid-state chemists designing and elaborating new intercalation electrodes to ensure that such an advantage endures over the next decades.

One recent advance that addresses the Li-ion battery as a whole is the plastic Li-ion battery. In addition to providing the performance of Li-ion liquid technology, the plastic Li-ion battery adds shape and performance design flexibility, enhances safety, and offers resistance to vibrations.

## 6.4 Plastic Li-ion Batteries

Current liquid-electrolyte Li-ion technology does not meet shape flexibility requirements dictated by portable electronics, and is limited to cylindrical or prismatic shapes. Rechargeable polymer Li batteries could provide shape flexibility, but after 20 years of research and development, the rechargeable polymer lithium battery technology still cannot function efficiently at room temperature, mostly because of the lack of polymer electrolytes with sufficient ionic conductivity.

Midway between rechargeable lithium batteries using liquid and those using pure polymer electrolytes are those using the hybrid electrolytes, for example, polymers swollen in liquid electrolytes (Fig. 6.8). These batteries combine the advantages of both liquid (high-power rate) and polymer electrolyte (no electrolyte leakage, easier scaleability) batteries. Reemerging during the last several years, the hybrid electrolyte concept was demonstrated by Feuillade and others<sup>52</sup> as early as 1974. In addition, the primary dry alkaline cells contain a liquid electrolyte that is “immobilized” in an elastic matrix.

The principle of electrolyte immobilization has also been applied to the recently popularized rechargeable lead-acid batteries known as VRLAs (valve regulated lead-acid batteries) in which the electrolyte is either in the form of a gel or absorbed in a silica mat separator. In the last several years, this concept has been widely applied in the field of rechargeable Li batteries to prepare a solid polymer electrolyte battery in which the electrolyte is immobilized in an appropriate polymer matrix. Hybrid polymer electrolyte films are usually made by dissolving a polymer matrix into a low boiling solvent (acetonitrile, tetrahydrofuran, etc.) together with a non-aqueous Li-salt electrolyte. The most popular polymer matrices<sup>53</sup> are polyethylene oxide (PEO) and its derivatives, such as polyacrylonitrile (PAN). Depending on the voltage range, a variety of liquid electrolytes were tried, with propylene carbonate (PC)-ethylene carbonate (EC)/Li-based salts being the most popular. The resulting viscous solution, consisting of the polymer matrix, low boiling solvent, and liquid electrolyte, is cast, usually resulting in tacky and mechanically weak films.

While many hybrid electrolytes reported in the literature exhibit high ionic conductivities, most exhibit various deficiencies preventing them from being used in practical cells. For example, their mechanical properties are often very poor, and the films must be hardened by either chemical or physical (high-energy radiation) curing. Besides the need for cross-linking, the main drawback

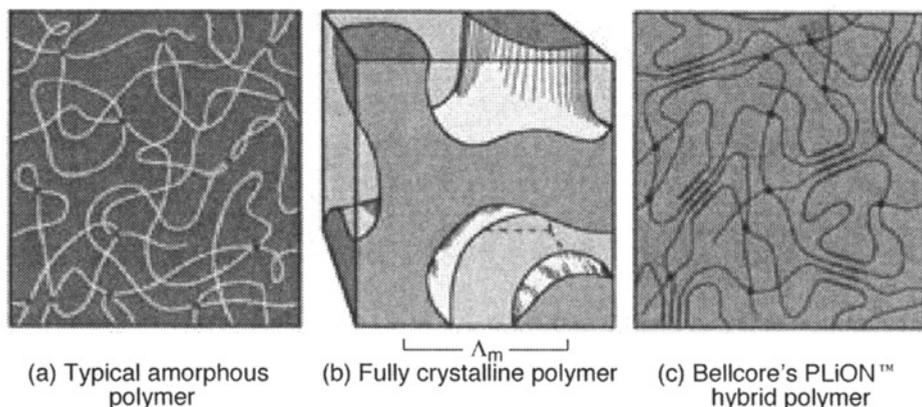


Fig. 6.8. Representation of three different approaches toward the polymer incorporation in Li-ion batteries: (a) amorphous swollen polymer; (b) fully crystalline polymer, which does not entrap the electrolyte; (c) Bellcore hybrid polymer, which combines the strength of the pure polymer and the electrolyte entrapment of the amorphous polymer.

of the above process is that it has to be carried out in a completely moisture-free atmosphere because the moisture-sensitive Li-salt is present at the initial stage. The manufacturing of such batteries requires advanced technologies for providing a low-humidity environment, thereby resulting in high processing costs.

Aiming to combine the recent commercial success enjoyed by liquid Li-ion batteries with the manufacturing advantages presented by polymer technology, Bellcore researchers introduced polymeric electrolytes in the liquid Li-ion system and developed the first reliable and practical rechargeable Li-ion plastic battery (Fig. 6. 9).<sup>54-56</sup>

A plastic is commonly defined as a combination of various material components, such as polymer matrix, plasticizers, fillers, stabilizers, and so on. These components are chosen in proportions, depending on the targeted application, to produce solid but elastic structures. Bellcore's plastic electrolyte complies with the above definition, the liquid electrolyte acting as the plasticizer. The correct choice of a polymer matrix is very important in the cell's manufacturability and longevity under extraneous operating conditions. The PLiON™ (Plastic Li-ion) battery uses a poly (vinylidene fluoride)-hexafluoropropylene (PVDF-HFP) copolymer (8–18% HFP). The Li<sup>+</sup> conduction is carried out by the liquid electrolyte embedded in the separator and the electrodes. The polymer remains chemically and electrochemically inactive. The polymer used as the matrix possesses several important characteristics:

- Chemically inert, with respect to electrode active materials and components of the plasticizer
- Electrochemically stable within the voltage range of interest (0–5 V vs Li)
- High melting/softening point, providing robustness in the final product
- Good mechanical stability for ease of processing and battery manufacturing
- Sufficient liquid electrolyte to provide good ionic conductivity
- Commercially available in large quantities at a low cost

PVDF-HFP copolymer consists of mixed amorphous and crystalline phases. Amorphous regions hold large amounts of liquid for high ionic conductivity, and crystalline domain provides the mechanical strength in the polymer film. Having the same polymer matrix throughout all the cell layers allows the fusion of the layers (Figs. 6.10 and 6.11) when laminated via heat and pressure, adding an unprecedented robustness to the cells, thereby eliminating the need for cross-linking. In addition, because of the fusion of the electrodes and separator, external stack pressure is not needed to ensure contact between the layers. Therefore, the cells can be assembled and packaged in a thin and soft metal laminate, providing a hermetic seal.<sup>57</sup>

Fabrication of a typical cell is as follows. The positive electrode composite is prepared by casting a slurry consisting of the transition metal positive electrode, conductive carbon black, PVDF-

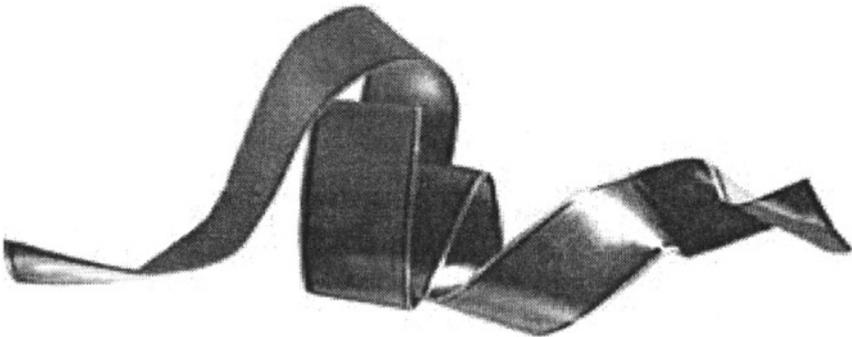


Fig. 6.9. The unpackaged PLiON™ battery.

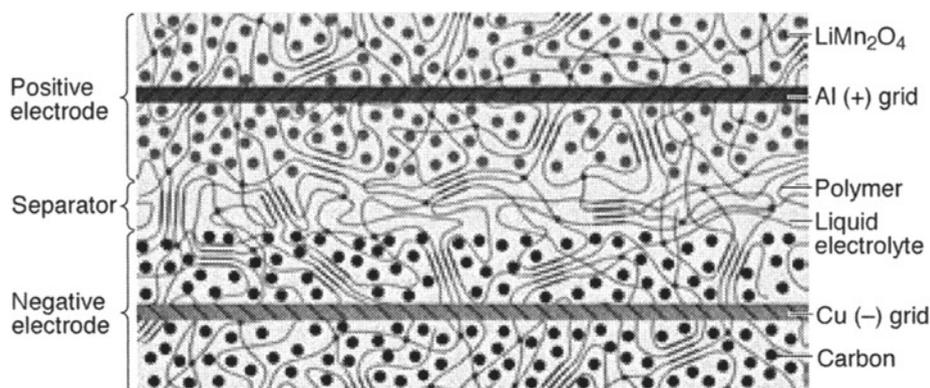


Fig. 6.10. Cross section of the PLiON™ battery. PVDF-HFP polymer and liquid electrolyte are dispersed throughout the entire battery assembly and are represented by lines and gray field, respectively.

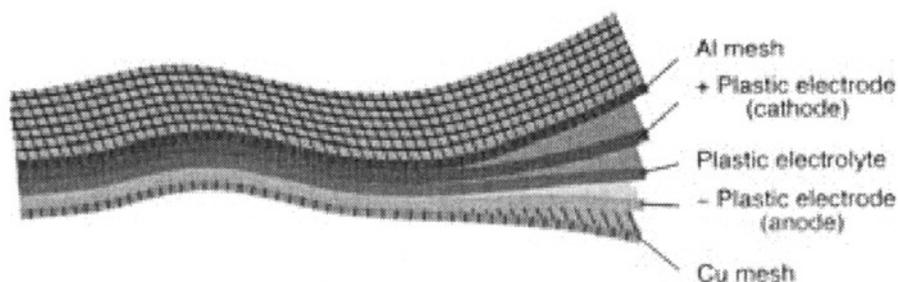


Fig. 6.11. The PLiON™ battery laminate showing the individual layers, which are laminated into one interface free structure.

HFP copolymer, dibutyl phthalate (DBP) plasticizer, and suitable solvent. The slurry is dried, and the resulting tape is laminated to an aluminum positive electrode grid. The negative electrode composite is prepared in very much the same way, except the transition metal positive electrode is replaced with a carbon-based negative electrode. The resulting negative tape is then laminated to a copper grid current collector. A separator is also cast, consisting of the PVDF-HFP copolymer, a filler, and DBP.

The positive laminate, the separator, and the negative laminate are then laminated between hot rollers to produce a bonded cell assembly with a continuous matrix of PVDF-HFP copolymer. The laminates can be made in any size, thickness, or shape. The completed cell is then placed in a bath of solvent to extract the DBP, which leaves a very fine continuous porosity (20 nm) throughout the polymer. Such a process lends itself to continuous manufacturing (Fig. 6.12).

All the fabrication steps to this point, unlike traditional plastic Li-ion batteries, are done under ambient conditions. To bypass the burden of assembling the cell in a moisture-free environment, the plastic laminate is activated at the very last stage through an extraction/activation step. The last step, cell activation, is performed in an atmosphere-controlled dry box. In this step the non-aqueous electrolyte is introduced into the cell. Since the porosity is very fine, capillary action soaks in the electrolyte without the need for degassing. The most important aspect of the PLiON™ battery is that the plastic laminate does not need to be made in a moisture-free environment. The only fabrication steps that require careful moisture control are the activation and packaging when

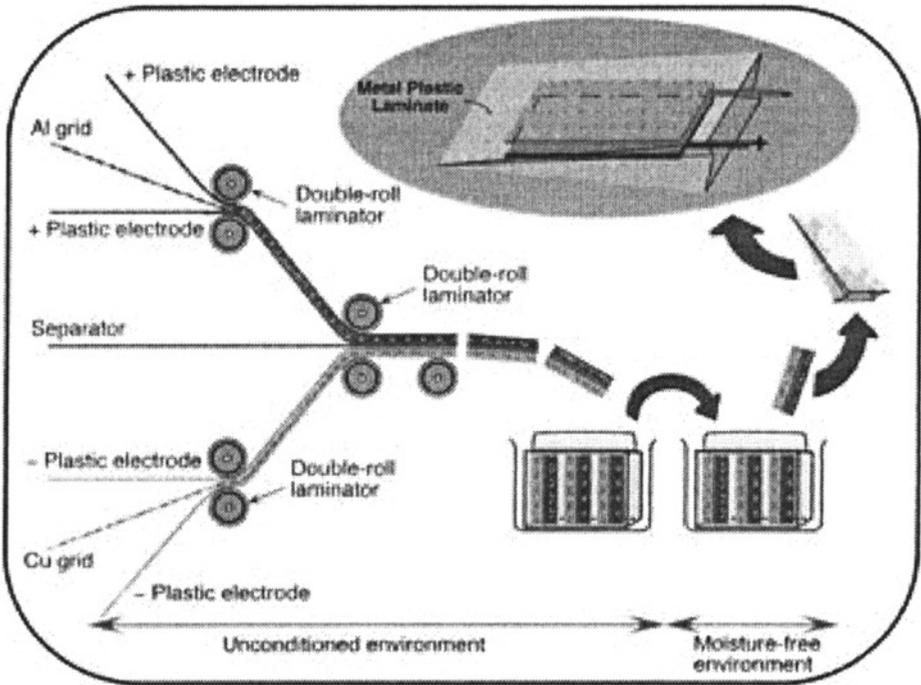


Fig. 6.12. Graphical representation of the PLiON™ battery fabrication process from initial positive electrode, negative electrode, and separator tapes to activated and packaged cell.

the moisture-sensitive lithium salt is present. It is important to remember that the PLiON™ battery performance is dictated by the Li-ion chemistry that is entrapped within the polymer matrix. Any combination of liquid electrolyte, positive electrode, and negative electrodes can be used within the PLiON™ battery. Figure 6.13 gives an example of the flexibility in chemistry by showing the performance of the PLiON™ battery using a number of different positive electrode materials.

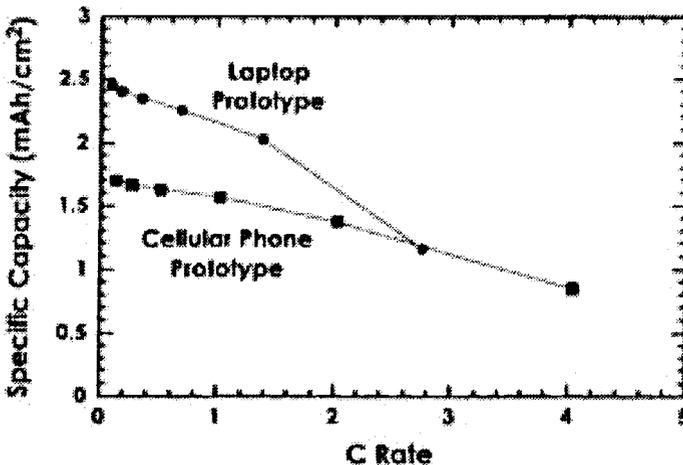


Fig. 6.13. Specific capacity vs C rate for PLiON™ batteries fabricated with thick and thin electrodes, showing the intrinsic performance flexibility of the technology based on application.

A unique and important feature of PLiON™ cells is that they can be designed for specific applications that have specific rate requirements. In a hybrid system, such as the PLiON™ battery, separator thickness plays a minor role in determining how fast the cells can charge or discharge (Fig. 6.14). The electrode thickness defines the initial cell capacity as well as the rate capability of each cell; this is a component that cannot be varied too much of a degree in today's liquid Li-ion technology. Therefore, PLiON™ cells can be designed to either optimize energy densities or rate capabilities, depending on the application.

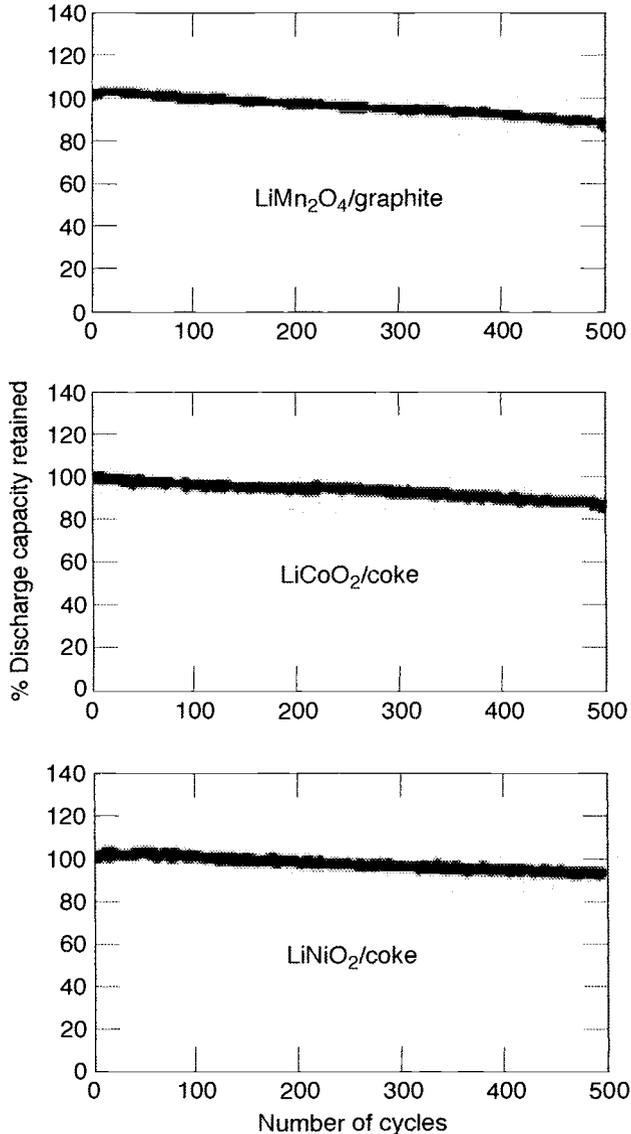


Fig. 6.14. Percent capacity as a function of cycle number showing the transparency of PLiON™ technology toward the incorporation of various positive electrode materials. PLiON™ technology is electrochemically inert and allows the incorporation of any variation of Li-ion chemistry.

PLiON™ technology combines the performance of the Li-ion batteries, which contain free liquid electrolyte, with the advantages of a polymer matrix. These batteries can be fabricated as flexible sheets or ribbons of different capacity of dimensions. The cells are thin, flat, flexible, shock- and vibration-proof. Unlike Li-ion batteries based on liquid technology, the main components of the PLiON™ battery are immobile and laminated into one solid composite. This offers advantage in situations involving large quantities of mechanically induced vibrations such as those developed during launch. The composite will be less prone to internal electrical disconnect and delamination. PLiON™ battery has high energy density, low weight, low self-discharge, long-cycle life both at room temperature and 55°C, and is environmentally benign (see Table 6.1 in Subsec. 8.3.3). In addition, these cells have low internal resistance, demonstrating low voltage drop at pulsed discharges of up to 3 C rate, maximizing the usable capacity at high rates. This performance is compared with that of high-rate NiCd technology in Fig. 6.15 for a consumer portable-phone application. In addition, the figures of merit of the plastic technology with its liquid counterparts and the Ni-based rechargeable systems are summarized in Table 6.1.

#### 6.4.1 The Plastic Battery and the Nanosatellite

Since Li-ion technology has not been proved during tens of thousands of cycles and publicized accelerated testing results are basically nonexistent, its implementation in space applications must first be targeted to GEO applications because of the limited number of eclipses and the relatively low number of cycles required from the battery.

The real advantage of the plastic technology resides in its design flexibility based on a plate type architecture. Current Li-ion technology relies on jellyrolling the three main components: positive and negative electrode and a separator. After this jellyroll is rolled under tension, the cell is placed into a cylindrical can, evacuated, and then filled with the non-aqueous electrolyte. Another derivative of the jellyroll is found in the liquid-based prismatic cells. In the construction of these small “brick-like” cells, an oval jellyroll is fabricated and fitted into prismatic cell housings.

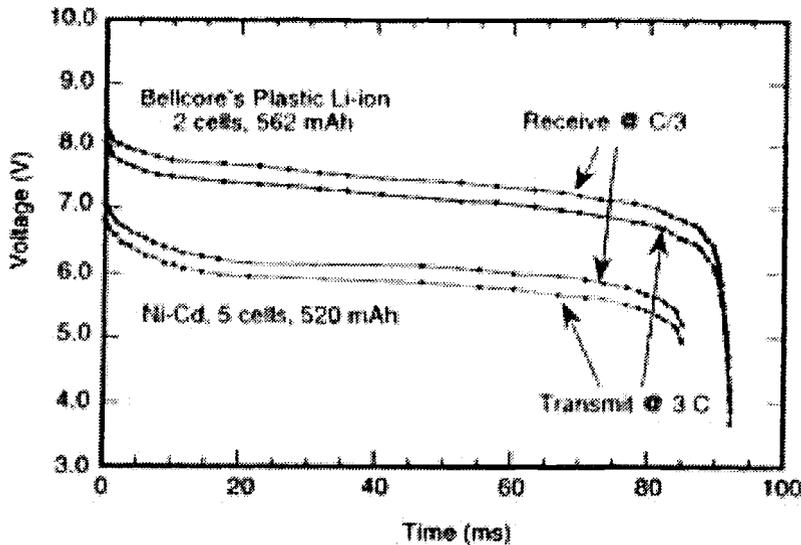


Fig. 6.15. Comparison of 3 C pulse rate performance of comparable PLiON™ and NiCd batteries.

Although such cells pack efficiently in a multiple cell configuration, the active components do not pack very efficiently inside the prismatic cell, as they are ovally wound jellyrolls inside rectangular, prismatic cans. The plate-like PLiON™ technology allows excellent packing efficiency, since multiple plates can be densely packaged in parallel within one cell. In addition, these multiple cells can then be placed in series or in parallel.

In specialty applications such as the nanosatellite, the plastic Li-ion battery can be designed in custom shapes that would maximize its use efficiency in a satellite of such design density. If powering requirements for the nanosatellite do not require voltages in excess of 4 V, single cells can be used in the application of Li-ion to the satellite, greatly simplifying the electronics and cell construction. The placement of such cells could be extreme, such as under solar cells, depending on the thermal conditions on which the cell would be exposed. Although these cells offer excellent design flexibility and performance, care must be taken to ensure proper environmental controls.

One of the first nanosatellites for planned launch is the ASUSat1, designed and developed by Arizona State University with the Aerospace Research Center.<sup>58</sup> The 10-lb nanosatellite will have a LEO and perform Earth imagery and AMSAT operations over its lifetime of 2 to 4 years. NiCd is the battery technology. Two battery packs are used; each consisting of six cells, presumably set in series to give an output voltage of 7.4 V. These cells are mounted in a rectangular foam box and mounted to an inside panel.

Using this as a case study, the adoption of the Li-ion plastic technology could result in significant advantages. Li-ion cells would occupy half the volume and one-third the weight of their Ni/Cd counterparts. This would free valuable space and weight for the implementation of additional analytical equipment in support of the satellite mission. Instead of having six individual Ni/Cd cells in series, which requires careful cell matching, the Li-ion cells would be able to deliver the required voltage using two cells. The Li-ion would not require any conditioning after partial discharge, as this technology exhibits no memory effect. The plastic cells offer exceptional design flexibility, allowing the most effective and efficient use of the volume of the satellite, as these cells can be manufactured in almost any 2D shape. The design flexibility offers an added benefit in thermal management. Passive thermal management is almost always maximized in satellite design, which is especially true in nanosatellite technology where volume and weight are at a premium. Therefore, the cell plates can be arranged and packaged in a material that would facilitate thermal management to a greater degree than traditional battery technology. Plates can be arranged so that thermal conduits can be placed between the high surface area stacks. These conduits can then eventually lead to a heat sink or exchanger.

The application of the PLiON™ battery also goes beyond the nanosatellite proper in support of the general nanosatellite program. One of the intents of the nanosatellite is to be independently controlled through remote ground links with devices such as personal laptops. The PLiON™ technology can be easily extended to these systems to offer lightweight, high-energy density powering systems. In fact such laptop batteries can be expected to enter the consumer market by early 1998. The cells will offer the performance advantages intrinsic to the Li-ion chemistry, with the added design flexibility of plastic.

## 6.5 Conclusion

Li-ion rechargeable battery technology possesses many beneficial attributes with respect to satellite powering issues. Although not perfect, Li-ion technology is superior to the current aqueous nickel technologies in both gravimetric and volumetric energy densities. In addition, this battery chemistry is relatively young and, in time, will show significant improvements in energy density.

Li-ion battery technology coupled with plastic Li-ion configuration (PLiON™) allows unprecedented flexibility in both physical and performance design. Such benefits in terms of weight, size, and design flexibility have much potential for design engineers striving to develop efficient, economical micro and nanosatellite technologies.

## 6.6 Acknowledgments

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## 6.7 References

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