

Handbook of Batteries

SECOND EDITION

David Linden

Electrical Engineering

*An update of the definitive guide to
all aspects of battery design and selection*

Handbook of Batteries

SECOND EDITION

Here is the one and only reference to offer you detailed data and information on the characteristics, properties, performance, and applications of all types of electric batteries.

Written by a staff of leading experts in battery technology, this essential working tool covers batteries for everything from small portable consumer items to electric vehicles and military and industrial equipment.

The new edition of the *Handbook of Batteries* shows you how to:

- Determine the performance characteristics of batteries under all conditions of use
- Establish the conditions and proper operating procedures to achieve optimum use of each battery system
- Select the most suitable battery for a given application

The Second Edition now features the latest data, tables, and figures covering the vast improvements in battery performance in recent years—and also explores new battery technologies, including lithium and rechargeable batteries.

Whether you're an engineer, technician, or product designer, the updated edition of this one-of-a-kind sourcebook enables you to take advantage of the many new advances in the fast-changing field of battery technology.

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HANDBOOK OF BATTERIES

David Linden Editor in Chief

Second Edition

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TABLE 23.3 Characteristics of the Major Secondary Battery Systems

Common name	Lead-acid				Nickel-cadmium			Nickel-iron (conventional)	Nickel-zinc
	SLI	Traction	Stationary	Portable	Vented pocket plate	Vented sintered plate	Sealed		
Chemistry:									
Anode	Pb	Pb	Pb	Pb	Cd	Cd	Cd	Fe	Zn
Cathode	PbO ₂	PbO ₂	PbO ₂	PbO ₂	NiOOH	NiOOH	NiOOH	NiOOH	NiOOH
Electrolyte	H ₂ SO ₄ (aqueous solution)	H ₂ SO ₄ (aqueous solution)	H ₂ SO ₄ (aqueous solution)	H ₂ SO ₄ (aqueous solution)	KOH (aqueous solution)	KOH (aqueous solution)	KOH (aqueous solution)	KOH (aqueous solution)	KOH (aqueous solution)
Cell voltage (typical), V:									
Nominal	2.0	2.0	2.0	2.0	1.2	1.2	1.2	1.2	1.6
Open circuit	2.1	2.1	2.1	2.1	1.29	1.29	1.29	1.37	1.73
Operating	2.0-1.8	2.0-1.8	2.0-1.8	2.0-1.8	1.25-1.00	1.25-1.00	1.25-1.00	1.25-1.05	1.6-1.4
End	1.75 (lower operating and end voltage during cranking operation)	1.75	1.75 (except when on float service)	1.75 (when cycled)	1.0	1.0	1.0	1.0	1.2
Operating temperature, °C	-40 to 55	-20 to 40	-10 to 40 ^c	-40 to 60	-20 to 45	-40 to 50	-40 to 45	-10 to 45	-20 to 60
Energy density (at 20°C):									
Wh/kg	35	25	10-20	30	20	37	30-35	27	60
Wh/L	70	80	50-70	90	40	90	80-105	55	120
Discharge profile (relative)	Flat	Flat	Flat	Flat	Flat	Very flat	Very flat	Moderately flat	Flat
Power density	High	Moderately high	Moderately high	High	High	High	Moderate to high	Moderate to low	High
Self-discharge rate (at 20°C), % loss per month ^b	20-30 (Sb-Pb) 2-3 (maintenance- free)	4-6	—	4-8	5	10	15-20	20-40	10
Calendar life, years	3-6	6	18-25	2-8	8-25	3-10	2-5	8-25	—
Cycle life, cycles ^c	200-700	1500	—	250-500	500-2000	500-2000	300-700	2000-4000	50-200
Advantages	Low cost, ready availability, good high-rate, high- and low- temperature operation (good cranking service), good float service, new maintenance-free designs	Lowest cost of competitive systems (also see SLI)	Designed for "float" service, lowest cost of competitive systems (also see SLI)	Maintenance- free; long life on float service; low- and high- temperature performance; no "memory" effect; operates in any position	Very rugged, can withstand physical and electrical abuse; good charge retention, storage and cycle life lowest cost of alkaline batteries	Rugged; excellent storage; good specific energy and high-rate and low- temperature performance	Sealed, no maintenance; good low- temperature and high-rate performance; long life cycle; operates in any position	Very rugged, can withstand physical and electrical abuse; long life (cycling or stand)	High energy density; relatively low cost; good low- temperature performance
Limitations	Relatively low cycle life; limited energy density; poor charge retention and storability; hydrogen evolution	Low energy density; less rugged than competitive systems; hydrogen evolution	Hydrogen evolution	Cannot be stored in discharged condition; lower cycle life than sealed nickel- cadmium; difficult to manufacture in very small sizes	Low energy density	High cost; "memory" effect; thermal runaway	Sealed lead-acid battery better at high temperature and float service; "memory" effect	Low power and energy density; high self- discharge; hydrogen evolution; high cost	Poor cycle life
Major cell types available	Prismatic cells: 30-200 Ah at 20-h rate	Based on positive plate design: 45- 200 Ah per positive plate	Based on positive plate design: 5- 400 Ah per positive plate	Sealed cylindrical cells: 2.5-25 Ah; prismatic cells: 0.9-35 Ah	Prismatic cells: 5-1300 Ah	Prismatic cells: 10-100 Ah	Button cells to 0.5 Ah; cylindrical cells to 10 Ah	New designs in development for EV and mobile traction	Not commercially available

^a Based on C/LiCoO₂ lithium-ion cell (see Chap. 36) (characteristics vary with battery system and design).^b Self-discharge rate usually decreases with increasing storage time.^c Dependent on depth of discharge.^d Low-rate Zn/AgO cell.

Nickel-cadmium			Nickel-iron (conventional)	Nickel-zinc	Zinc/silver oxide (silver-zinc)	Cadmium/ silver oxide (silver-cadmium)	Nickel- hydrogen	Nickel-metal hydride	Rechargeable "primary" types, Zn/MnO ₂	Lithium systems (lithium-ion) ^a
Vented sintered plate	Sealed									
Cd NiOOH KOH (aqueous solution)	Cd NiOOH KOH (aqueous solution)	Zn NiOOH KOH (aqueous solution)	Zn AgO KOH (aqueous solution)	Cd AgO KOH (aqueous solution)	H ₂ NiOOH KOH (aqueous solution)	MH NiOOH KOH (aqueous solution)	Zn MnO ₂ KOH (aqueous solution)	C LiCoO ₂ Organic solvent		
1.2 1.29 1.25-1.00 1.0	1.2 1.29 1.25-1.00 1.0	1.2 1.37 1.25-1.05 1.0	1.6 1.73 1.6-1.4 1.2	1.5 1.85 1.7-1.3 1.0	1.2 1.4 1.4-1.0 0.7	1.4 1.32 1.3-1.15 1.0	1.2 1.4 1.25-1.10 1.0	1.5 1.5 1.3-1.0 1.0	4.0 4.2 4.0-2.5 2.5	
5	-40 to 50	-40 to 45	-10 to 45	-20 to 60	-20 to 60	-25 to 70	0 to 50	-20 to 50	-20 to 40	-20 to 55
37 90 Very flat	30-35 80-105 Very flat	27 55 Moderately flat	60 120 Flat	90 180 Double plateau	55 100 Double plateau	55 60 Moderately flat	50 175 Flat	85 250 Sloping	90 200 Sloping	
High	Moderate to high	Moderate to low	High	High (for high rate-designs)	Moderate to high	Moderate	Moderate to high	Moderate	Moderate	
10	15-20	20-40	10	3	3	60	20		5-10	
3-10	2-5	8-25	—	1-3 ^d	2-3	—	2-5			
00	500-2000	300-700	200-4000	50-200	100-150 ^d	150-600	1500-6000	300-600	15-25	500-1000
d, nd d buse; e d west aline	Rugged; excellent storage; good specific energy and high-rate and low- temperature performance	Sealed, no maintenance; good low- temperature and high-rate performance; long life cycle; operates in any position	Very rugged, can withstand physical and chemical abuse; long life (cycling or stand)	High energy density; relatively low cost; good low- temperature performance	Highest energy density; high discharge rate; low self- discharge	High energy density; low self-discharge; good cycle life	High energy density; long cycle life at high DOD; can tolerate overcharge	High energy density; sealed, operates	Good shelf life; low cost	High specific energy; good shelf life
y	High cost; "memory" effect; thermal runaway	Sealed lead-acid battery better at high temperature and float service; "memory" effect	Low power and energy density; high self- discharge; open solution; high cost	Poor cycle life	High cost; low cycle life; decreased performances at low temperatures	High cost; decreased performance at low temperatures	High initial cost; self-discharge proportional to H ₂ pressure	High cost (may be limited to special military and aerospace applications)	Limited cycle life; low drain applications; small size only	Low rate (compared to aqueous systems)
cells: 1	Prismatic cells: 10-100 Ah	Button cells to 0.5 Ah; cylindrical cells to 10 Ah	New designs in development for EV and motive traction	Not commercially available	Prismatic cells: <1 to 800 Ah; special types to 6000 Ah	Prismatic cells: <1 to 500 Ah	Mainly for aerospace applications (up to 100 Ah)	Button and cylindrical cells	Cylindrical cells	Cylindrical and prismatic cells

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23.2.3 Advanced Batteries

Finally, the need for higher energy density, better charge retention, and other improved characteristics has created an unparalleled interest in the development of new, more advanced secondary battery systems. These fall into several general groups:

1. Ambient temperature systems that are stable in aqueous electrolytes, using zinc, aluminum, or magnesium as the negative active materials.
2. Ambient temperature systems using lithium or other alkali metals as the active materials but requiring nonaqueous, aprotic electrolytes as the aqueous electrolytes are reactive with these metals.
3. High-temperature systems, also using lithium or other alkali metals as the active materials. These systems use molten salt or ceramic electrolytes and operate at high temperatures ranging from 200 to 450°C.

These advanced systems are covered in Part 5.

23.3 COMPARISON OF PERFORMANCE CHARACTERISTICS FOR SECONDARY BATTERY SYSTEMS

23.3.1 General

The characteristics of the major secondary systems are summarized in Table 23.3. This table is supplemented by Tables 1.2 and 6.2, which list several theoretical and practical electrical characteristics of these secondary battery systems. A graphic comparison of the theoretical and practical performances of various battery systems is given in Fig. 3.1. This shows that up to only about 20–30% of the theoretical capacity of a battery system is attained under practical conditions as a result of design and the discharge requirements.

It should be noted, as discussed in detail in Chaps. 3 and 6, that these types of data and comparisons (as well as the performance characteristics shown in this section) are necessarily approximations, with each system being presented under favorable discharge conditions. The specific performance of a battery system is very dependent on the cell design and all the detailed and specific conditions of the use and discharge-charge of the battery.

A qualitative comparison of the various secondary battery systems is presented in Table 23.4. The different ratings given to the various designs of the same electrochemical system are an indication of the effects of the design on the performance characteristics of a battery.

23.3.2 Voltage and Discharge Profiles

The discharge curves of the conventional secondary battery systems, at the $C/5$ rate, are compared in Fig. 23.2. The lead-acid battery has the highest cell voltage of the

TABLE 23.4 Comparison

System	Energy density
Lead-acid:	
Pasted	4
Tubular	4
Planted	5
Sealed	4
Lithium-metal	1
Lithium-ion	2
Nickel-cadmium:	
Pocket	5
Sintered	4
Sealed	4
Nickel-iron	5
Nickel-metal hydride	3
Nickel-zinc	2
Silver-zinc	1
Silver-cadmium	2
Nickel-hydrogen	2
Silver-hydrogen	2
Zinc-manganese dioxide	2

* Rating: 1 to 5, best to poor

conventional system 1.65 V for the nickel. relatively little difference given system. However, differences could be

Most of the conventional except for the silver oxide electrode the silver oxide electrode

The discharge curve of the silver oxide system, is shown higher than those of the lithium anode. The lower conductivity of the electrode. The discharge curves of the batteries are discussed

23.3.3 Energy Density

The delivered energy of the cells and batteries are compared with the theoretical energy

The silver oxide and nickel-hydrogen cells show the significant differences under various conditions

TABLE 23.4 Comparison of Secondary Batteries*

System	Energy density	Power density	Flat discharge profile	Low-temperature operation	Charge retention	Charge acceptance	Efficiency	Life	Mechanical properties	Cost
Lead-acid:										
Pasted	4	4	3	3	4	3	2	3	5	1
Tubular	4	5	4	3	3	3	2	2	3	2
Plated	5	5	4	3	3	3	2	2	4	2
Sealed	4	3	3	2	3	3	2	3	5	2
Lithium-metal	1	3	3	2	1	3	3	4	3	4
Lithium-ion	2	3	3	2	2	2	2	2	3	3
Nickel-cadmium:										
Pocket	5	3	2	1	2	1	4	2	1	3
Sintered	4	1	1	1	4	1	3	2	1	3
Sealed	4	1	2	1	4	2	3	3	2	2
Nickel-iron	5	5	4	5	5	2	5	1	1	3
Nickel-metal hydride	3	2	2	1	4	2	3	3	2	3
Nickel-zinc	2	3	2	3	4	3	3	4	3	3
Silver-zinc	1	2	5	3	1	5	1	5	3	4
Silver-cadmium	2	3	5	4	1	5	1	4	3	4
Nickel-hydrogen	2	3	3	4	5	3	5	2	3	5
Silver-hydrogen	2	3	4	4	5	3	5	2	3	5
Zinc-manganese dioxide	2	4	5	3	1	4	4	5	4	2

* Rating: 1 to 5, best to poorest.

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conventional systems. The average voltage of the alkaline systems ranges from about 1.65 V for the nickel-zinc system to about 1.1 V. At the C/5 discharge rate at 20°C there is relatively little difference in the shape of the discharge curve for the various designs of a given system. However, at higher discharge rates and at lower temperatures, these differences could be significant, depending mainly on the internal resistance of the cell.

Most of the conventional rechargeable battery systems have a flat discharge profile, except for the silver oxide systems, which show the double plateau due to the discharge of the silver oxide electrode, and the rechargeable zinc/manganese dioxide battery.

The discharge curve of one of the rechargeable lithium cells, the lithium/manganese dioxide system, is shown for comparison. The cell voltages of the lithium cells are usually higher than those of the conventional aqueous cells because of the characteristics of the lithium anode. The discharge profile of the lithium cells is usually not as flat due to the lower conductivity of the nonaqueous electrolytes that must be used with the lithium electrode. The discharge characteristics of the lithium and other advanced secondary batteries are discussed in Part 5.

23.3.3 Energy Density

The delivered energy densities, both gravimetric and volumetric, of the various secondary cells and batteries are shown graphically in Fig. 23.3. The values can also be compared with the theoretical values for these systems given in Table 1.2.

The silver oxide systems deliver the highest capacities, followed by the nickel-zinc and nickel-hydrogen cells and finally by the nickel-cadmium and lead-acid systems. These data show the significance of the cell and battery design on the energy output as well as the conditions under which the battery is discharged. Accordingly, there is a wide range and

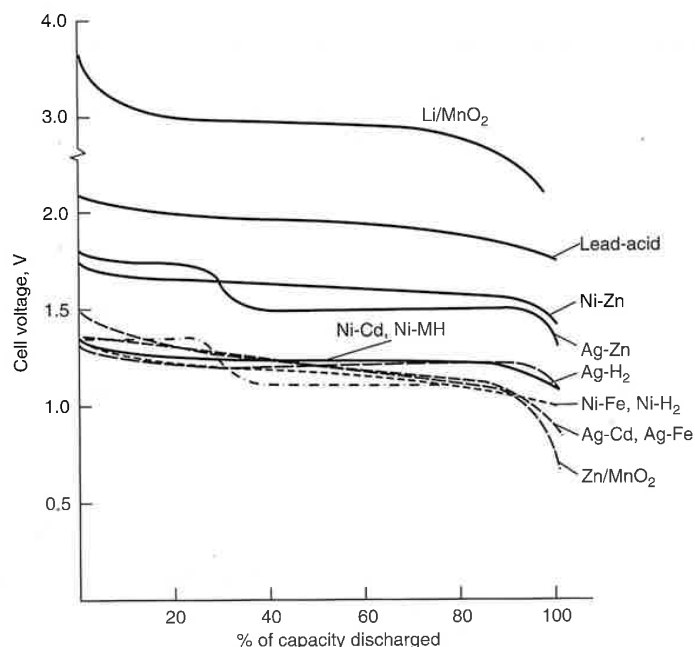


FIGURE 23.2 Discharge profiles of conventional secondary battery systems and rechargeable Li/MnO₂ cell at approximately $C/5$ discharge rate.

even an overlap in performance, indicating the need to consider all of the conditions of operation before making a choice of battery system and design.

Advanced rechargeable batteries, using lithium and other high-energy materials (covered in Part 5), have the potential of higher energy densities, ranging up to about 125 Wh/kg and 275 Wh/L.

23.3.4 Effect of Discharge Rate on Energy Density

In Fig. 23.4 the effect of the discharge rate on the performance of each battery system is compared based on the watt-hour capacity for each system (capacity at 0.1C rate = 100%). With the exception of the conventional nickel-iron battery, which was not designed for high-rate performance, the capacity of the alkaline batteries decreases relatively little with increasing discharge rate compared with the lead-acid system. This is due to the limited time available for the diffusion of the sulfuric acid electrolyte during a high-rate discharge of the lead-acid battery. The sintered-plate nickel-cadmium system shows the best performance.

The performance of the rechargeable lithium/manganese dioxide cell is also shown. While the energy density of this system is higher at the relatively low discharge rates, this capacity decreases with increasing discharge rates more significantly than the conventional aqueous secondary batteries.

The effects of the discharge rate on the performance of these secondary battery systems are compared again in Fig. 23.5. This figure is similar to a Ragone plot, except that the

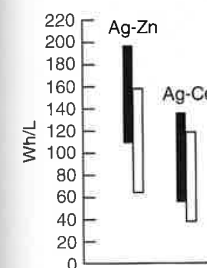
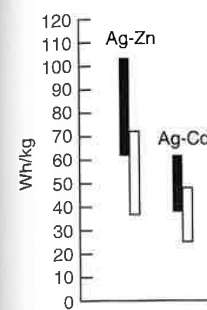


FIGURE 23.3 Energy density. (b) Volumetric

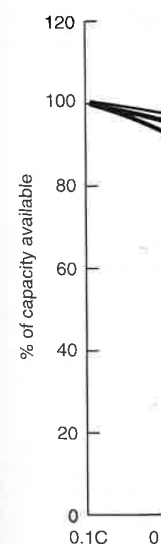


FIGURE 23.4 Effect of discharge rate on the percentage of capacity available at 20°C.

The solid polymer electrolyte technology provides flexibility in battery design as the cell can be fabricated in a variety of shapes, forms, configurations, and sizes. The estimated specific energy and the energy density, up to 200 Wh/kg and 385 Wh/L, are very attractive. To date, however, cells have been fabricated only in small sizes, and none have been commercialized. Major interest is in using this battery system for applications requiring high voltages and capacity. This will require significant scaling up of the current technology, which presents a manufacturing challenge because of the thin components and the uniformity standards that will be required.⁴³

At present, solid-state rechargeable lithium polymer electrolyte cells using lithium anodes have limited cycle life and rate capability. The limited rate capability of these batteries is due to the lower ionic conductivity, low lithium transport number, and poor electrode-electrolyte interface properties. The cause for the limited cycle life is not completely understood, but could be due to degradation of the presently used cathode materials, irreversible lithium intercalation into the cathode materials, high reactivity of the polymeric electrolytes toward the anode and cathode materials, or the formation of lithium dendrites.

Solid polymer electrolytes have also been used with anodes other than metallic lithium, such as lithiated carbon in a lithium-ion cell (see Sec. 36.4.3). These cells may have lower capacity but may provide some of the advantages of the lithium-ion technology, such as longer cycle life and greater safety, and minimize potential problems due to the use of metallic lithium and the formation of dendritic lithium, which may form during repeated cycling of a lithium anode cell.

36.4.3 Lithium-Ion Cells

The lithium-ion rechargeable cell refers to a cell whose negative active material is a carbon to which lithium cations are intercalated or deintercalated during the charge-discharge process, rather than metallic lithium or a lithium alloy. The positive active material is a lithiated metallic oxide intercalation compound from or into which a lithium ion can be extracted or inserted, respectively, during charge and discharge. LiCoO_2 , LiNiO_2 , and LiMn_2O_4 are attractive materials, with advantages such as stability in air, high voltage, and reversibility for the lithium insertion reaction. LiCoO_2 was used in most of the initial work on the lithium-ion technology and was the first system commercialized. This material is easiest to prepare and holds its structure during cycling. LiNiO_2 is less expensive than LiCoO_2 , is more stable at higher temperatures, and has a lower self-discharge rate. It is anticipated that ultimately the industry will move to a manganese-based material, such as LiMn_2O_4 , as these materials are more abundant, inexpensive, and nontoxic. The early lithium-ion cells used liquid organic electrolytes, but both liquid organic and solid polymer electrolytes (SPE) are used, similar to the electrolytes in the metallic lithium anode cells. SO_2 -based electrolytes are also being investigated (see Sec. 36.4.4).

The general characteristics and the chemistry of the lithium-ion cell are described in Secs. 36.2.3 and 36.3. Some of their electrical characteristics are listed in Table 36.12.

The lithium-ion cells, using the positive active materials identified earlier, have high voltages ranging from 3.0 to 4.0 V. A comparison of the discharge voltage profiles of cells using these positive electrode materials with petroleum coke and graphite negative electrode materials is shown in Fig. 36.31. The sloping discharge profile is characteristic of the lithium-ion cells using the disordered coke type carbon materials, compared to the flatter discharge profile of the cells using graphite.

At present the graphite-anode cells usually have a higher capacity at low discharge rates than the petroleum coke cells, but they lose this advantage at the higher current drains. This is probably due to the potential drop across the space charge region of graphite and to the need to use a compatible ethylene carbonate-based electrolyte, which has a lower

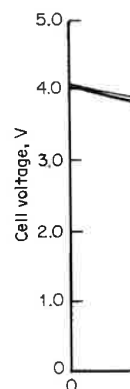


FIGURE 36.3 Comparison of petroleum coke and graphite negative electrode materials.

Ga

Insulc

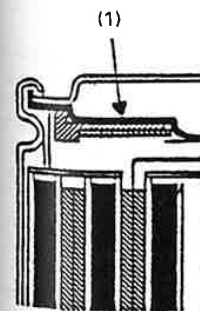


FIGURE 36.32 (a) Cross-sectional diagram of a cell showing a vent mechanism for limiting. (1) Aluminum layer.

design as the cell es. The estimated are very attractive. I none have been lications requiring p of the current n components and

cells using lithium apability of these number, and poor cycle life is not ntly used cathode, high reactivity of r the formation of

an metallic lithium, lls may have lower echnology, such as due to the use of m during repeated

material is a carbon re charge-discharge active material is a lithium ion can be CoO_2 , LiNiO_2 , and ir, high voltage, and t of the initial work ed. This material is less expensive than discharge rate. It is ed material, such as ontoxic. The early ic and solid polymer lithium anode cells.

cell are described in in Table 36.12. d earlier, have high tage profiles of cells d graphite negative le is characteristic of ls, compared to the

t low discharge rates igher current drains. on of graphite and to, which has a lower

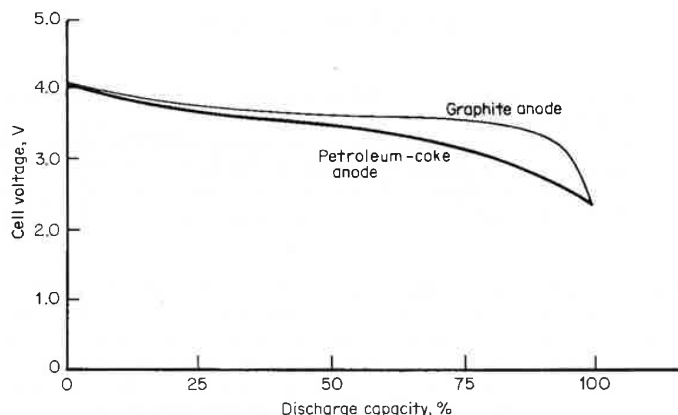


FIGURE 36.31 Discharge characteristics of a C/LiCoO_2 lithium-ion cell comparison of petroleum-coke and graphite anodes.

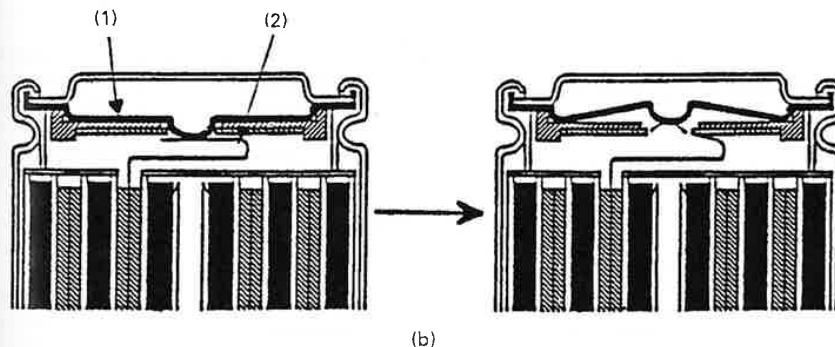
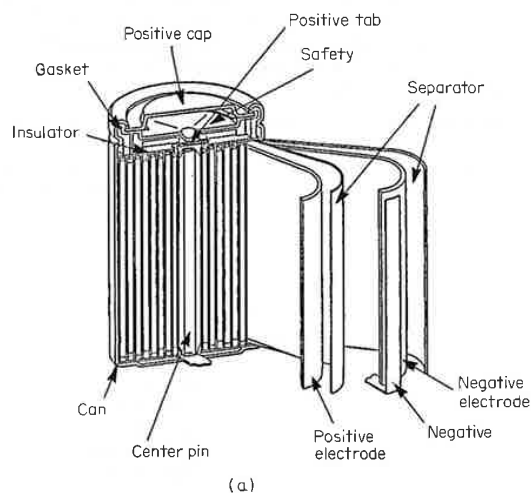


FIGURE 36.32 (a) Construction of a lithium-ion cell. (b) Detail of current breaker mechanism as well as a vent mechanism for an abnormal rise of internal pressure in case of overcharging with no voltage limiting. (1) Aluminum burst disk. (2) Aluminum lead. (From Sony Corp.)

conductivity than other electrolytes. The diffusion coefficient of Li^+ into graphite is about two orders of magnitude lower than that in petroleum coke.

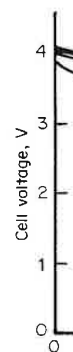
The lithium-ion cell can be designed in any of the typical cell constructions: flat or coin, spirally wound cylindrical, or prismatic configurations. While most of the developments to date have concentrated on the smaller cells for portable applications, larger prismatic cells are under investigation for applications ranging up to power levels required for electric vehicles.

Carbon/Lithium Cobalt Oxide Cells. These cells use the spirally wound cylindrical construction, as shown in Fig. 36.32. The cell is fabricated with the active material in the discharged state. The positive electrode is made by coating a thin aluminum foil collector with the lithiated metal oxide compound (LiCoO_2) for the active material.⁴⁶⁻⁴⁸ Metal-doped (Al, In, or Sn) LiCoO_2 has also been used as a cathode.^{49,50} The current collector of the negative electrode is a thin copper foil onto which a petroleum coke type carbon material is coated for the active material. Graphitic carbon, however, delivers much higher capacity.^{47,48} The electrolyte consists of an organic solvent, such as propylene carbonate-diethyl carbonate, in which a salt such as LiPF_6 has been dissolved. LiBF_4 has also been used as the electrolyte.⁵⁰ The electrodes are rolled up in a "jelly-roll" configuration with a polypropylene separator between them. The cell contains a safety vent to release any pressure that may develop if the cell is overcharged or otherwise abused. Some cells contain a positive temperature coefficient device to protect the cell against excessive currents that may occur during discharge, charge, or short circuits.

The design parameters of a lithium-ion cell, using a nongraphitized carbon anode and a LiCoO_2 cathode, are listed in Table 36.17. The discharge characteristics, at various discharge rates and temperatures, are plotted in Fig. 36.33. The cell has a high voltage, ranging from about 4 to 2.7 V during discharge, and a sloping discharge profile.

TABLE 36.17 Typical Design Parameters for C/ LiCoO_2 Cylindrical Cell (Size 18650)

Cathode			
Active material:	LiCoO_2	Thickness (total):	0.018 cm
Binder:	PVDF	Cathode length:	49.5 cm
Loading (total):	11.57 g	Substrate length:	52.0 cm
		width:	5.4 cm
Current collector:	Al foil (25 μm)	Area (both sides):	535 cm^2
Leads:	Al		
Anode			
Active material:	Nongraphitized carbon	Thickness (total):	0.020 cm
Binder:	PVDF	Anode length:	51.1 cm
Loading (total):	4.92 g	Substrate length:	53.7 cm
		width:	5.4 cm
Current collector:	Cu foil (25 μm)	Area (both sides):	552 cm^2
Other Components			
Electrolyte:	PC/DEC, LiPF_6		
Separator:	Celgard (25 μm)		
Insulator:	PP disk		
Leads:	Aluminum		
Case:	Nickel-plated steel		
Header:	Aluminum safety vent		
Closure:	Crimp		



Cell voltage, V

FIGURE 36.33 Discharge characteristics of C/ LiCoO_2 cylindrical cell at 0.2C rate.

Continuous discharge up to the 5–6C rate is a problem due to internal resistance drop during the discharge. The internal resistance of other batteries in the market is much lower.

The shelf life of metallic lithium cells at 20°C, but it is restored with cycling.

Lithium-ion cells control the charging voltages may cause

o graphite is about
actions: flat or coin,
he developments to
rger prismatic cells
equired for electric

wound cylindrical
ative material in the
ninum foil collector
material.⁴⁶⁻⁴⁸ Metal-
current collector of
a coke type carbon
delivers much higher
opylene carbonate-
LiBF₄ has also been
configuration with a
vent to release any
abused. Some cells
all against excessive

carbon anode and a
steristics, at various
has a high voltage,
g discharge profile.

e 18650)

0.018 cm
49.5 cm
52.0 cm
5.4 cm
535 cm²

0.020 cm
51.1 cm
53.7 cm
5.4 cm
552 cm²

I
vent

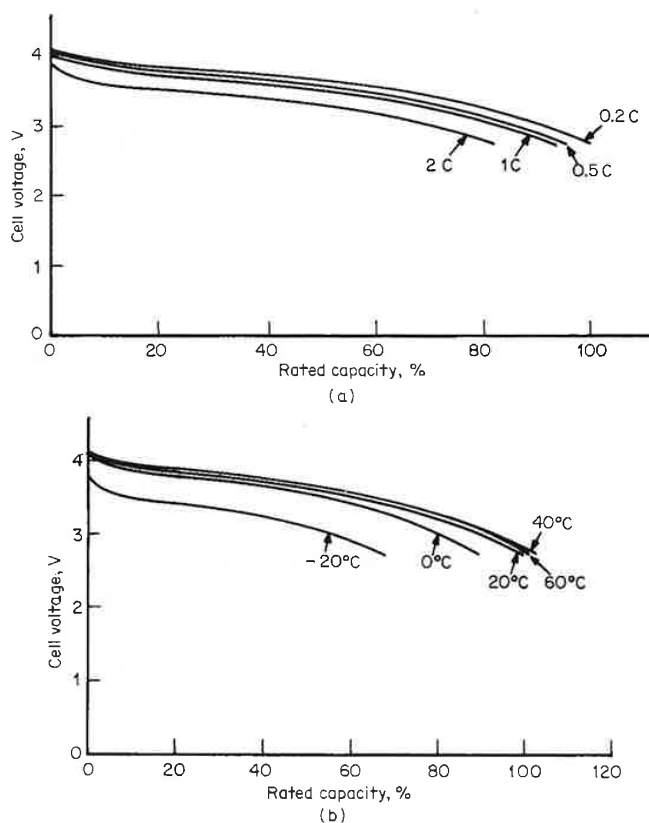


FIGURE 36.33 Discharge curves of C/LiCoO₂ lithium-ion cell (nongraphitized carbon anode). Charge limited to 4.1 V. (a) Discharge at 20°C. (b) Discharges at 0.2C rate at various temperatures. (From Sony Corp.)

Continuous discharge currents can be as high as the 1.5–2C rate, with pulse discharges of up to the 5–6C rate. Overdischarging should be avoided as it may cause a performance problem due to internal short-circuiting resulting from the corrosion of the anode current collector. The internal impedance is relatively constant during the discharge. The voltage drop during the discharge results from potential changes in the negative electrode, unlike other batteries in which the drop in voltage is due to an increase in the cell's impedance.

Figure 36.34 shows the discharge characteristics of a C/LiCoO₂ cell using a graphite anode. The discharge profile of these cells is flatter than that of the cells using petroleum coke.

The shelf life or charge retention of these lithium-ion cells is poorer than that of the metallic lithium cells. For the C/LiCoO₂ cell it can be as high as 10% per month of storage at 20°C, but it is lower with the other cathode materials. The capacity of the cell can be restored with cycling.

Lithium-ion cells are capable of being recharged quickly within 1–2 h. It is necessary to control the charging voltage for the LiCoO₂ cell to about 4.2 V per cell. Higher charge voltages may cause the decomposition of the electrolyte at the positive electrode with a

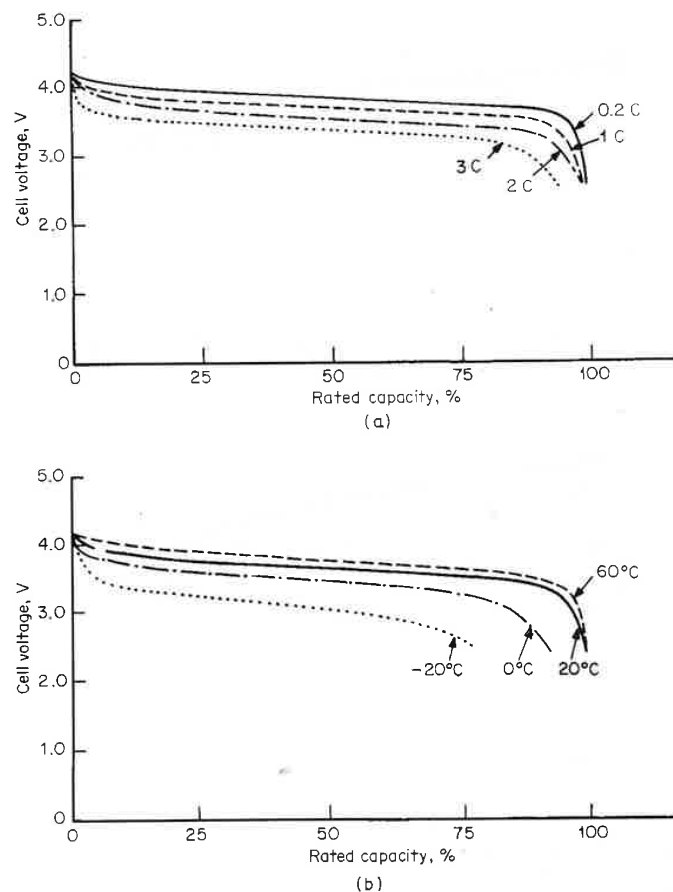


FIGURE 36.34 Discharge characteristics of C/LiCoO₂ lithium-ion cell (graphite anode). (a) Discharges at 20°C. (b) Discharges at 0.2C rate at various temperatures. (From Sanyo Energy Corp.)

rise in the internal pressure and the plating of lithium on the carbon surface. Figure 36.35 shows the voltage and current characteristics of a modified constant-current charge at several charge rates, with the maximum charge voltage limited to 4.2 V. The temperature range during charge should be between 0 and 45°C.

Typically the cycle life of the lithium-ion cell is superior to that of the metallic lithium rechargeable cells. Over 500 cycles can be obtained to 75% of rated capacity, as shown in Fig. 36.35b.

Lithium-ion (C/LiCoO₂) cells are commercially available in a spirally wound cylindrical configuration. The physical and electrical characteristics of some of these cells are listed in Table 36.18. Manufacturers' data sheets should be consulted for more recent and detailed information.

The C/LiCoO₂ system has also been examined in other configurations. The discharge

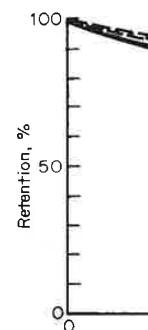


FIGURE 36.35b current rate to 4.2

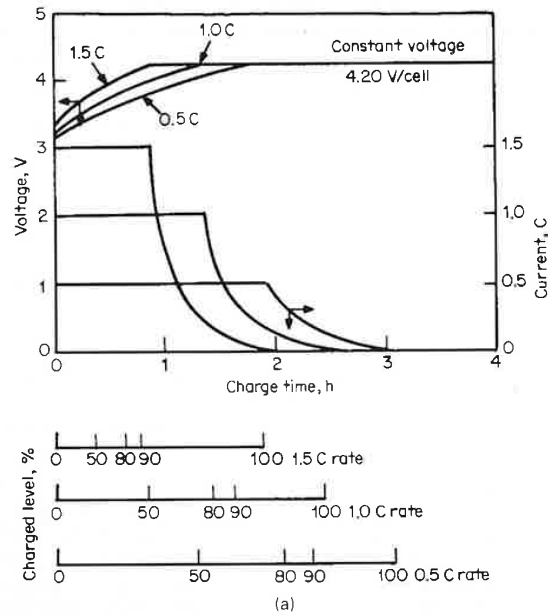


FIGURE 36.35a Charging characteristics of a C/LiCoO₂ lithium-ion cell at 20°C. Constant current charge (at 0.5, 1.0, and 1.5 C rate) to 4.2 V/cell. (From A&T Battery Corp.)

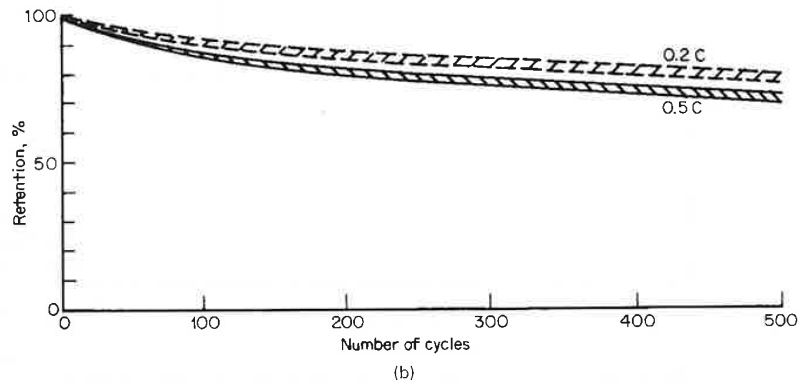


FIGURE 36.35b Cycle life of a C/LiCoO₂ lithium-ion cell at 25°C. Charging: 1C constant current rate to 4.2 V for 3 h; discharge at 0.2C and 0.5C rate. (From A&T Battery Corp.)

TABLE 36.18 Electrical Characteristics of Typical C/LiCoO₂ Cells*

Type	14500	16530	17500	18650	20500	652248	863448	143448	40488
Shape	Cylindrical	Cylindrical	Cylindrical	Cylindrical	Cylindrical	Prismatic	Prismatic	Prismatic	Prismatic
Size, mm									
Height	50	53.0	50.0	65.0	50.0	48.0	48.0	48.0	48.0
Diameter	14.5	16.0	17.0	17.7	20.0				
Length						22.0	34.0	34.0	40.0
Width						6.5	8.6	14.5	8.0
Volume, cm ³	8.3	10.7	11.3	16.5	15.7	6.9	14.0	23.6	15.4
Weight, g	18	28	26	40	39	20	40	65	41
Capacity, mAh	450	640	700	1200	1200	380	730	1300	850
Specific energy, Wh/kg	90	85	100	110	110	70	65	70	75
Energy density, Wh/L	195	215	225	260	275	195	185	195	195

* Normal voltage 4.0 V, average voltage 3.6 V.

behavior at different current drains of a prismatic-D C/LiCoO₂ cell is shown in Fig. 36.36a.⁵¹ The average operating voltage of the cell is over 3.7 V at C/4 rate. The cell provides a specific energy of 84 Wh/kg and an energy density of 225 Wh/L with newer designs delivering over 100 Wh/kg and 260 Wh/L. In a bipolar design, the lithium-ion system has demonstrated high-rate capability, delivering more than 3000 high-rate pulse cycles (see Fig. 36.36b) with little effect of short-range overcharge-overdischarge on performance and safety.⁵²

Carbon/Lithium Nickel Oxide Cells. Lithium nickel oxide is another popular positive electrode for lithium-ion cells. This cell operates at a slightly lower voltage than the

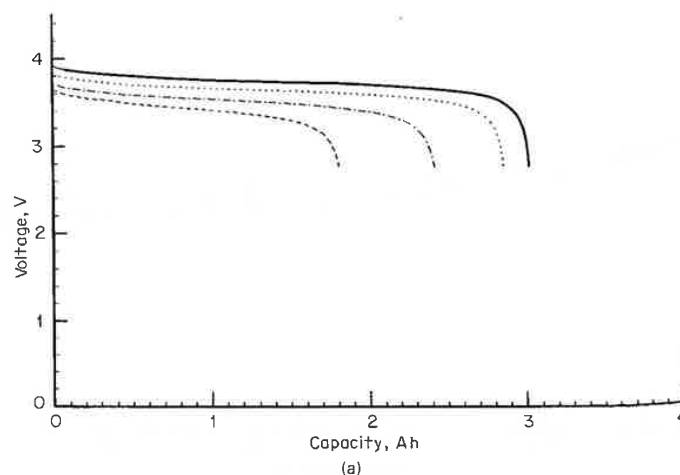


FIGURE 36.36a Discharge behavior of a prismatic Li-ion cell at different current drains. Cathode: LiCoO₂; anode: graphite. —, 750 mA; ···, 1000 mA; - · - ·, 2000 mA; ---, 3000 mA. (From Yardeny Technical Products, Inc.)



FIGURE 3
cycles, 45 n
LiCoO₂; an

C/LiCoO₂ cell, but elevated temperature

Cells have been designed with various features of a design features of a at various discharge is sloping, typical of summary of the d discharge rates and for the LiCoO₂ cell may lose from 1 to

The charge and 36.39. Figure 36.39a potentials. The op

TABLE 36.19 Typical

Case Header
Vent Closure
Fill and seal
Current collectors
Active materials
Separator
Typical active area

SOURCE: Rayovac