10

Batteries

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10.1 Introduction

The battery is an essential component of almost all aircraft electrical systems. Batteries are used to start engines and auxiliary power units, to provide emergency backup power for essential avionics equipment, to assure no-break power for navigation units and fly-by-wire computers, and to provide ground power capability for maintenance and preflight checkouts. Many of these functions are mission critical, so the performance and reliability of an aircraft battery is of considerable importance. Other important requirements include environmental ruggedness, a wide operating temperature range, ease of maintenance, rapid recharge capability, and tolerance to abuse.

Historically, only a few types of batteries have been found to be suitable for aircraft applications. Until the 1950s, vented lead-acid (VLA) batteries were used exclusively [Earwicker, 1956]. In the late 1950s, military aircraft began converting to vented nickel-cadmium (VNC) batteries, primarily because of their superior performance at low temperature. The VNC battery subsequently found widespread use in both military and commercial aircraft [Fleischer, 1956; Falk and Salkind, 1969]. The only other type of battery used during this era was the vented silver-zinc battery, which provided an energy density about three times higher than VLA and VNC batteries [Miller and Schiffer, 1971]. This battery type was applied to several types of U.S. Air Force fighters (F-84, F-105, and F-106) and U.S. Navy helicopters (H-2, H-13, and H-43) in the 1950s and 1960s. Although silver-zinc aircraft batteries were attractive for reducing weight and size, their use has been discontinued due to poor reliability and high cost of ownership.

In the late 1960s and early 1970s, an extensive development program was conducted by the U.S. Air Force and Gulton Industries to qualify sealed nickel-cadmium (SNC) aircraft batteries for military and commercial applications [McWhorter and Bishop, 1972]. This battery technology was successfully demonstrated on a Boeing KC-135, a Boeing 727, and a UH-1F helicopter. Before the technology could be transitioned into production, however, Gulton Industries was taken over by SAFT and a decision was made to terminate the program.

In the late 1970s and early 1980s, the U.S. Navy pioneered the development of sealed lead-acid (SLA) batteries for aircraft applications [Senderak and Goodman, 1981]. SLA batteries were initially applied to the AV-8B and F/A-18, resulting in a significant reliability and maintainability (R&M) improvement compared with VLA and VNC batteries. The Navy subsequently converted the C-130, H-46, and P-3 to SLA batteries. The U.S. Air Force followed the Navy's lead, converting numerous aircraft to SLA batteries, including the A-7, B-1B, C-130, C-141, KC-135, F-4, and F-117 [Vutetakis, 1994]. The term "High Reliability, Maintenance-Free Battery,"or HRMFB, was coined to emphasize the improved R&M capability of sealed-cell aircraft batteries. The use of HRMFBs soon spun off into the commercial sector, and numerous commercial and general aviation aircraft today have been retrofitted with SLA batteries.

In the mid-1980s, spurred by increasing demands for HRMFB technology, a renewed interest in SNC batteries took place. A program to develop advanced SNC batteries was initiated by the U.S. Air Force, and Eagle-Picher Industries was contracted for this effort [Flake, 1988; Johnson et al., 1994]. The B-52 bomber was the first aircraft to retrofit this technology. SNC batteries also have been developed by ACME for several aircraft applications, including the F-16 fighter, Apache AH-64 helicopter, MD-90, and Boeing 777 [Anderman, 1994].

A recent development in aircraft batteries is the "low maintenance"or "ultra-low maintenance"nickel-cadmium battery [Scardaville and Newman, 1993]. This battery is intended to be a direct replacement of conventional VNC batteries, avoiding the need to replace or modify the charging system. Although the battery still requires scheduled maintenance for electrolyte filling, the maintenance frequency can be decreased significantly. This type of battery has been under development by SAFT and more recently by Marathon. Limited flight tests have been performed by the U.S. Navy on the H-1 helicopter. Application of this technology to commercial aircraft is also being pursued.

Determining the most suitable battery type and size for a given aircraft type requires detailed knowledge of the application requirements (load profile, duty cycle, environmental factors, and physical constraints) and the characteristics of available batteries (performance capabilities, charging requirements, life expectancy, and cost of ownership). With the various battery types available today, considerable expertise is required to size, select, and prepare technical specifications. The information contained in this chapter will provide general guidance for original equipment design and for upgrading existing aircraft batteries. More detailed information can be found in the sources listed at the end of the chapter.

10.2 General Principles

10.2.1 Battery Fundamentals

Batteries operate by converting chemical energy into electrical energy through electrochemical discharge reactions. Batteries are composed of one or more cells, each containing a **positive electrode, negative electrode, separator,** and **electrolyte**. Cells can be divided into two major classes: primary and secondary. Primary cells are not rechargeable and must be replaced once the reactants are depleted. Secondary cells are rechargeable and require a DC charging source to restore reactants to their fully charged state. Examples of primary cells include carbon-zinc (Leclanche or dry cell), alkaline-manganese, mercury-zinc, silver-zinc, and lithium cells (e.g., lithium-manganese dioxide, lithium-sulfur dioxide, and lithium-thionyl chloride). Examples of secondary cells include lead-lead dioxide (lead-acid), nickel-cadmium, nickel-iron, nickel-hydrogen, nickel-metal hydride, silver-zinc, silver-cadmium, and lithium-ion. For aircraft applications, secondary cells are the most prominent, but primary cells are sometimes used for powering critical avionics equipment (e.g., flight data recorders).

Batteries are rated in terms of their **nominal voltage** and **ampere-hour capacity**. The voltage rating is based on the number of cells connected in series and the nominal voltage of each cell (2.0 V for lead-acid and 1.2 V for nickel-cadmium). The most common voltage rating for aircraft batteries is 24 V. A 24-V lead-acid battery contains 12 cells, while a 24-V nickel-cadmium battery contains either 19 or 20 cells (the U.S. military rates 19-cell batteries at 24 V). Voltage ratings of 22.8, 25.2, and 26.4 V are also common with nickel-cadmium batteries, consisting of 19, 20, or 22 cells, respectively. Twelve-volt lead-acid batteries, consisting of six cells in series, are also used in many general aviation aircraft.

The ampere-hour (Ah) capacity available from a fully charged battery depends on its temperature, rate of discharge, and age. Normally, aircraft batteries are rated at room temperature (25°C), the **C-rate** (1-hour rate), and beginning of life. Military batteries, however, often are rated in terms of the end-of-life capacity, i.e., the minimum capacity before the battery is considered unserviceable. Capacity ratings of aircraft batteries vary widely, generally ranging from 3 to 65 Ah.

The maximum power available from a battery depends on its internal construction. High rate cells, for example, are designed specifically to have very low internal impedance as required for starting turbine engines and auxiliary power units (APUs). Unfortunately, no universally accepted standard exists for defining the peak power capability of an aircraft battery. For lead-acid batteries, the peak power typically is defined in terms of the cold-cranking amperes, or **CCA** rating. For nickel-cadmium batteries, the peak power rating typically is defined in terms of the current at maximum power, or **Imp** rating. These ratings are based on different temperatures (−18°C for CCA, 23°C for Imp), making it difficult to compare different battery types. Furthermore, neither rating adequately characterizes the battery's initial peak current capability, which is especially important for engine start applications. More rigorous peak power specifications have been included in some military standards. For example, MIL-B-8565/15 specifies the initial peak current, the current after 15 s, and the capacity after 60 s, during a 14-V constant voltage discharge at two different temperatures (24 and −26°C).

The **state-of-charge** of a battery is the percentage of its capacity available relative to the capacity when it is fully charged. By this definition, a fully charged battery has a state-of-charge of 100% and a battery with 20% of its capacity removed has a state-of-charge of 80%. The **state-of-health** of a battery is the percentage of its capacity available when fully charged relative to its rated capacity. For example, a battery rated at 30 Ah, but only capable of delivering 24 Ah when fully charged, will have a state-of-health of $24/30 \times 100 = 80\%$. Thus, the state-of-health takes into account the loss of capacity as the battery ages.

10.3 Lead-Acid Batteries

10.3.1 Theory of Operation

The chemical reactions that occur in a lead-acid battery are represented by the following equations:

$$\text{Positive electrode: } PbO_2 + H_2SO_4 + 2H^+ + 2e^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} PbsO_4 + 2H_2O \tag{1}$$

$$\text{Negative electrode: } Pb + H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} PbSO_4 + 2H^+ + 2e^- \tag{2}$$

$$\text{Overall cell reaction: } PbO_2 + pb + 2H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} 2PbSO_4 + 2H_2O \tag{3}$$

As the cell is charged, the sulfuric acid (H_2SO_4) concentration increases and becomes highest when the cell is fully charged. Likewise, when the cell is discharged, the acid concentration decreases and becomes most dilute when the cell is fully discharged. The acid concentration generally is expressed in terms of specific gravity, which is weight of the electrolyte compared to the weight of an equal volume of pure water.

The cell's specific gravity can be estimated from its open circuit voltage using the following equation:

$$\text{Specific Gravity (SG)} = \text{Open Circuit Voltage (OCV)} - 0.84 \tag{4}$$

There are two basic cell types: vented and recombinant. Vented cells have a flooded electrolyte, and the hydrogen and oxygen gases generated during charging are vented from the cell container. Recombinant cells have a starved or gelled electrolyte, and the oxygen generated from the positive electrode during charging diffuses to the negative electrode where it recombines to form water by the following reaction:

$$Pb + H_2SO_4 + 1/2O_2 \rightarrow PbSO_4 + H_2O \tag{5}$$

The recombination reaction suppresses hydrogen evolution at the negative electrode, thereby allowing the cell to be sealed. In practice, the recombination efficiency is not 100% and a resealable valve regulates the internal pressure at a relatively low value, generally below 10 psig. For this reason, sealed lead-acid cells are often called "valve-regulated lead-acid" (VRLA) cells.

10.3.2 Cell Construction

Lead-acid cells are composed of alternating positive and negative plates, interleaved with single or multiple layers of separator material. Plates are made by pasting active material onto a grid structure made of lead or lead alloy. The electrolyte is a mixture of sulfuric acid and water. In flooded cells, the separator material is porous rubber, cellulose fiber, or microporous plastic. In recombinant cells with starved electrolyte technology, a glass fiber mat separator is used, sometimes with an added layer of microporous polypropylene. Gell cells, the other type of recombinant cell, are made by absorbing the electrolyte with silica gel that is layered between the electrodes and separators.

10.3.3 Battery Construction

Lead-acid aircraft batteries are constructed using injection-molded, plastic **monoblocs** that contain a group of cells connected in series. Monoblocs typically are made of polypropylene, but ABS is used by at least one manufacturer. Normally, the monobloc serves as the battery case, similar to a conventional automotive battery. For more robust designs, monoblocs are assembled into a separate outer container made of steel, aluminum, or fiberglass-reinforced epoxy. Cases usually incorporate an electrical receptacle for connecting to the external circuit with a quick connect/disconnect plug. Two generic styles of receptacles are common: the "Elcon style" and the "Cannon style." The Elcon style is equivalent to military type MS3509. The Cannon style has no military equivalent, but is produced by Cannon and other connector manufacturers. Batteries sometimes incorporate thermostatically controlled heaters to improve low temperature performance. The heater is powered by the aircraft's AC or DC bus. Figure 10.1 shows an assembly drawing of a typical lead-acid aircraft battery; this particular example does not incorporate a heater.

10.3.4 Discharge Performance

Battery performance characteristics usually are described by plotting voltage, current, or power vs. discharge time, starting from a fully charged condition. Typical discharge performance data for SLA aircraft batteries are illustrated in Figures 10.2 and 10.3. Figure 10.4 shows the effect of temperature on the capacity when discharged at the C-rate. Manufacturers' data should be obtained for current information on specific batteries of interest.

10.3.5 Charge Methods

Constant voltage charging at 2.3 to 2.4V per cell is the preferred method of charging lead-acid aircraft batteries. For a 12-cell battery, this equates to 27.6 to 28.8 V which generally is compatible with the voltage available from the aircraft's 28-V DC bus. Thus, lead-acid aircraft batteries normally can be charged by direct connection to the DC bus, avoiding the need for a dedicated battery charger. If the voltage regulation on the DC bus is not controlled sufficiently, however, the battery will be overcharged or undercharged causing premature failure. In this case, a regulated voltage source may be necessary to achieve acceptable battery life. Some aircraft use voltage regulators that compensate, either manually or automatically, for the battery temperature by increasing the voltage when cold and decreasing the voltage when hot.

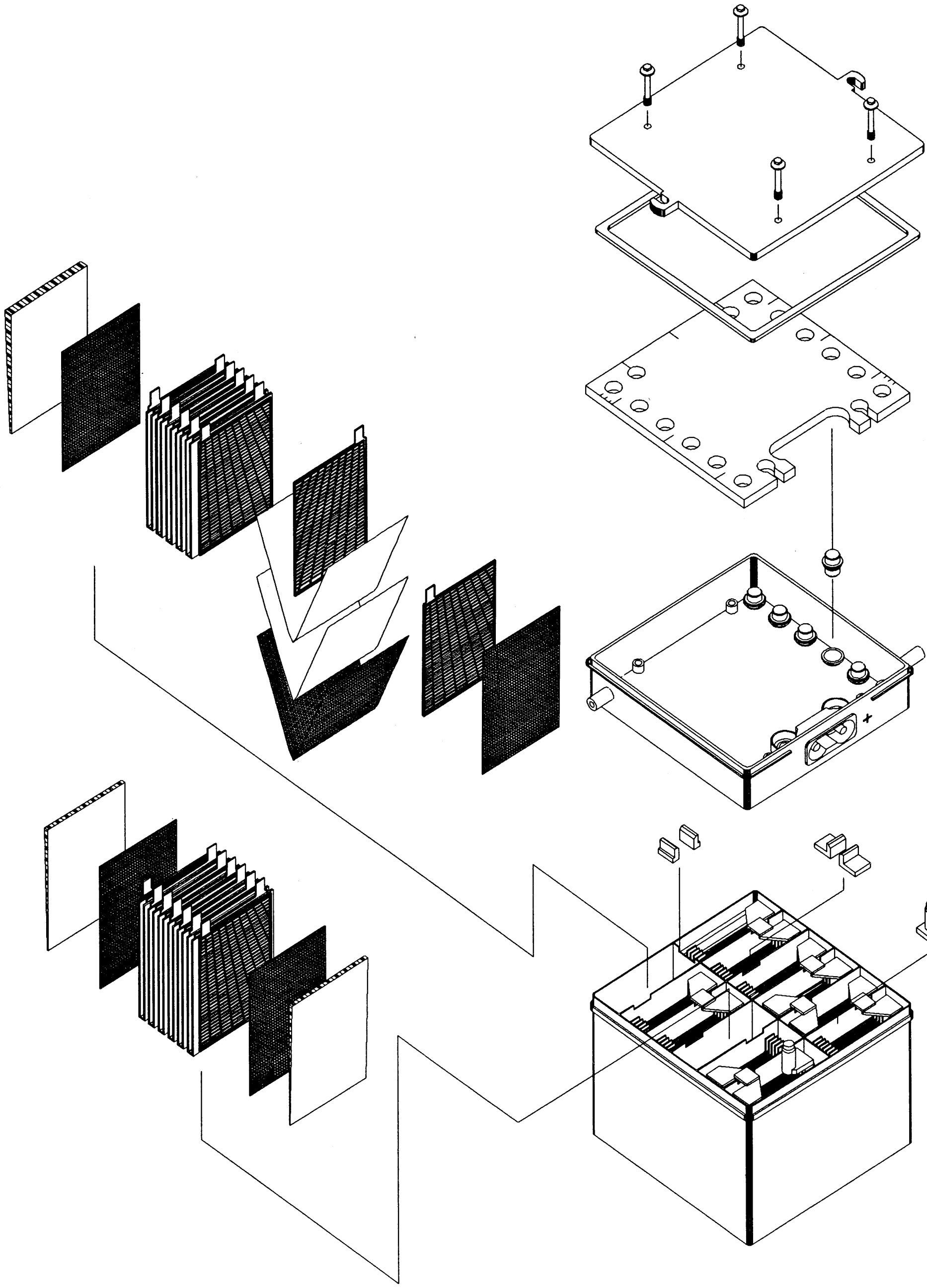


FIGURE 10.1 Assembly drawing of a lead-acid aircraft battery.

Adjusting the charging voltage in this manner has the beneficial effect of prolonging the battery's service life at high temperature and achieving faster recharge at low temperatures.

10.3.6 Temperature Effects and Limitations

Lead-acid batteries generally are rated at 25°C (77°F) and operate best around this temperature. Exposure to low ambient temperatures results in performance decline, whereas exposure to high ambient temperatures results in shortened life.

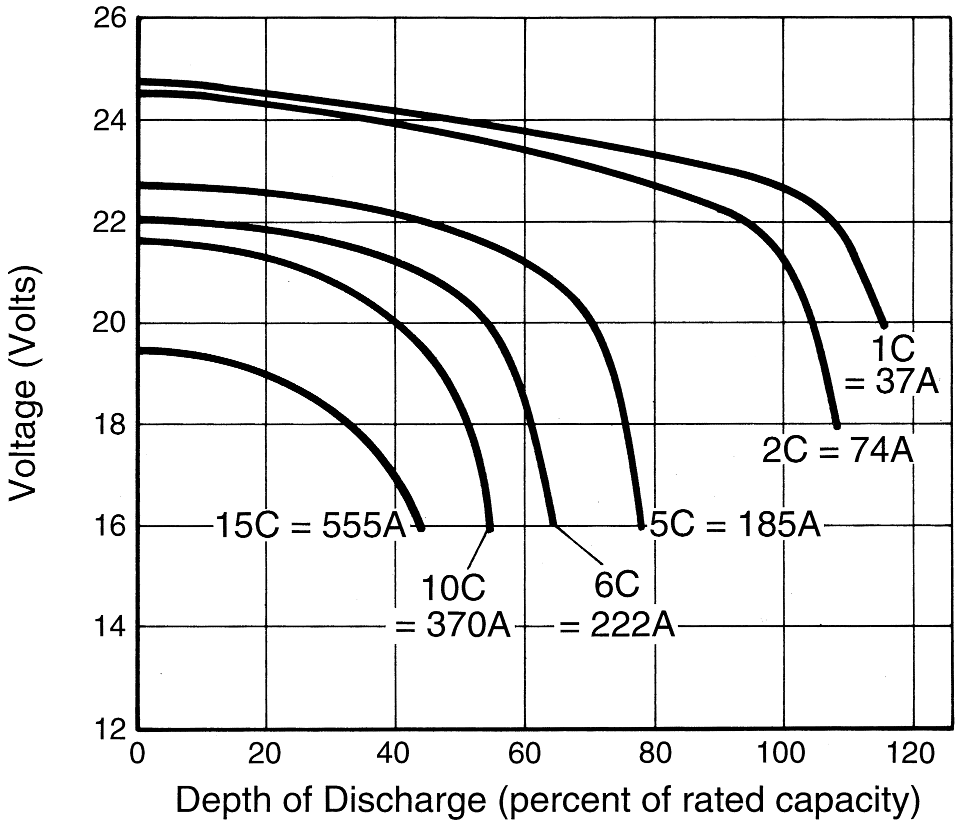


FIGURE 10.2 Discharge curves at 25°C for a 24 V/37 Ah SLA aircraft battery.

The lower temperature limit is dictated by the freezing point of the electrolyte. The electrolyte freezing point varies with acid concentration, as shown in Table 10.1. The minimum freezing point is a chilly 70°C (−95°F) at a specific gravity (SG) of 1.30. Since fully charged batteries have SGs in the range of 1.28 to 1.33, they are not generally susceptible to freezing even under extreme cold conditions. However, when the battery is discharged, the SG drops and the freezing point rises. At low SG, the electrolyte first will turn to slush as the temperature drops. This is because the water content freezes first, gradually raising the SG of the remaining liquid so that it remains unfrozen. Solid freezing of the electrolyte in a discharged battery requires temperatures well below the slush point; a practical lower limit of −30°C is often specified. Solid freezing can damage the battery permanently (i.e., by cracking cell containers), so precautions should be taken to keep the battery charged or heated when exposed to temperatures below −30°C.

The upper temperature limit is generally in the range of 60 to 70°C. Capacity loss is accelerated greatly when charged above this temperature range due to vigorous gassing and/or rapid grid corrosion. The capacity loss generally is irreversible when the battery is cooled.

10.3.7 Service Life

The service life of a lead-acid aircraft battery depends on the type of use it experiences (e.g., rate, frequency, and depth of discharge), environmental conditions (e.g., temperature and vibration), charging method, and the care with which it is maintained. Service lives can range from 1 to 5 years, depending on the application. Table 10.2 shows representative life cycle data as a function of the depth of discharge. Manufacturers' data should be consulted for specific batteries of interest.

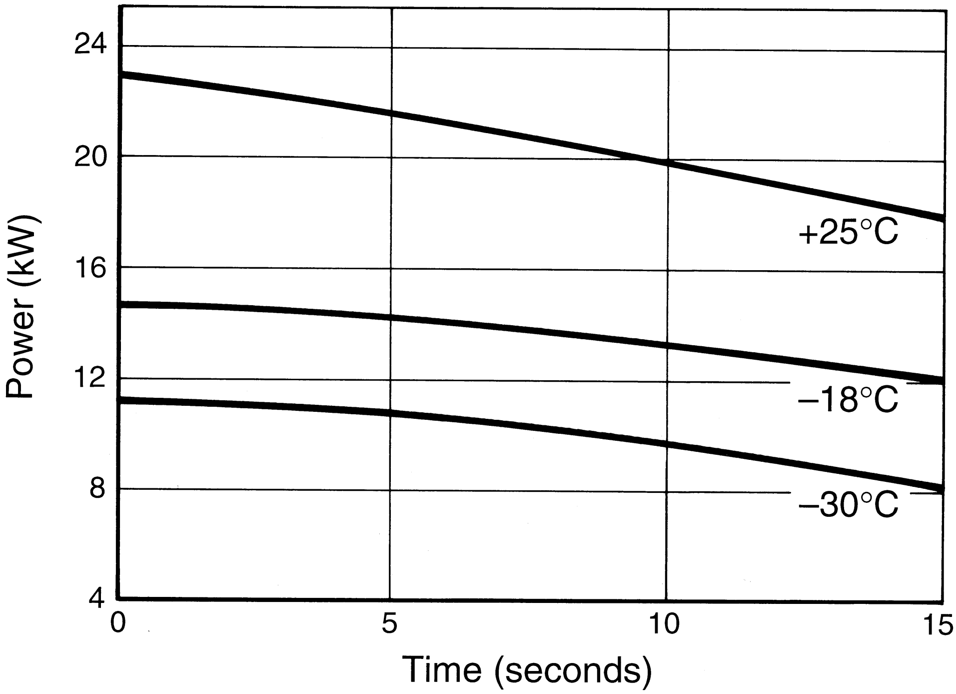


FIGURE 10.3 Maximum power curves (12 V Discharge) for a 24 V/37 Ah SLA battery.

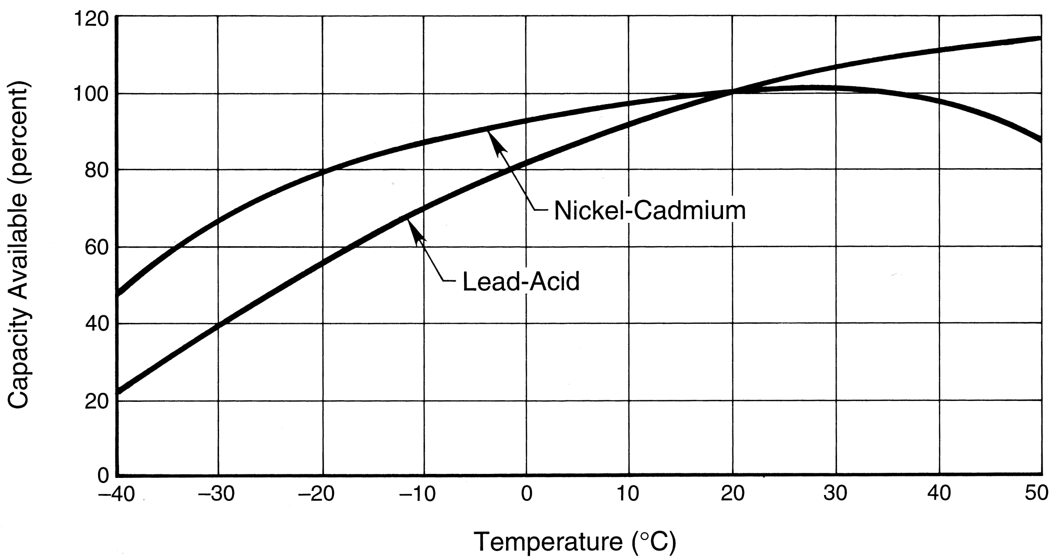


FIGURE 10.4 Capacity vs. temperature for aircraft batteries at the C-rate.

10.3.8 Storage Characteristics

Lead-acid batteries always should be stored in the charged state. If allowed to remain in the discharged state for a prolonged time period, the battery becomes damaged by "sulfation." Sulfation occurs when lead sulfate forms into large, hard crystals, blocking the pores in the active material. The sulfation creates

TABLE 10.1 Freezing Points of Sulfuric Acid-Water Mixtures

Specific Gravity at 15° C	Cell OCV (Volts)	Battery OCV (Volts)	Freezing Point (°C)	(°F)
1.000	1.84	22.08	0	+32
1.050	1.89	22.68	−3	+26
1.100	1.94	23.28	−8	+18
1.150	1.99	23.88	−15	+5
1.200	2.04	24.48	−27	−17
1.250	2.09	25.08	−52	−62
1.300	2.14	25.68	−70	−95
1.350	2.19	26.28	−49	−56
1.400	2.24	26.88	−36	−33

TABLE 10.2 Cycle Life Data for SLA Aircraft Batteries

Depth of Discharge (% of Rated Capacity)	Number of Cycles to End of Life
10	2000
30	670
50	400
80	250
100	200

Source: Hawker Energy Products.

a high impedance condition that makes it difficult for the battery to accept recharge. The sulfation may or may not be reversible, depending on the discharge conditions and specific cell design. The ability to recovery from deep discharge has been improved in recent years by electrolyte additives, such as sodium sulfate.

VLA batteries normally are supplied in a dry, charged state (i.e., without electrolyte), which allows them to be stored almost indefinitely (i.e., 5 years or more). Once activated with electrolyte, periodic charging is required to overcome the effect of self-discharge and to prevent sulfation. The necessary charging frequency depends on the storage temperature. At room temperature (25°C), charging every 30 days is typically recommended. More frequent charging is necessary at higher temperatures (e.g., every 15 days at 35°C), and less frequent charging is necessary at low temperatures (e.g., every 120 days at 10°C).

SLA batteries can be supplied only in the activated state (i.e., with electrolyte), so storage provisions are more demanding compared with dry charged batteries. As in the case of activated VLA batteries, periodic charging is necessary to overcome the effects of self-discharge and to prevent sulfation. The rate of self-discharge of SLA batteries varies widely from manufacturer to manufacturer, so the necessary charging frequency also varies widely. For example, recommended charging frequencies can range from 3 to 24 months.

10.3.9 Maintenance Requirements

Routine maintenance of lead-acid aircraft batteries is required to assure airworthiness and to maximize service life. For vented-cell batteries, electrolyte topping must be performed on a regular basis to replenish the water loss that occurs during charging. Maintenance intervals are typically 2 to 4 months. A capacity test or load test usually is included as part of the servicing procedure. For sealed-cell batteries, water replenishment obviously is unnecessary, but periodic capacity measurements generally are recommended. Capacity check intervals can be based either on calendar time (e.g., every 3 to 6 months after the first year) or operating hours (e.g., every 100 hours after the first 600 hours). Refer to the manufacturer's maintenance instructions for specific batteries of interest.

10.3.10 Failure Modes and Fault Detection

The predominant failure modes of lead-acid cells are summarized as follows:

- Shorts caused by growth on the positive grid, shedding or mossing of active material, or mechanical defects protruding from the grid, manifested by inability of the battery to hold a charge (rapid decline in open circuit voltage).
- Loss of electrode capacity due to active material shedding, excessive grid corrosion, sulfation, or passivation, manifested by low capacity and/or inability to hold voltage under load.
- Water loss and resulting cell dry-out due to leaking seal, repeated cell reversals, or excessive overcharge (this mode applies to sealed cells or to vented cells that are improperly maintained), manifested by low capacity and/or inability to hold voltage under load.

Detection of these failure modes is straightforward if the battery can be removed from the aircraft. The battery capacity and load capability can be measured directly and the ability to hold a charge can be inferred by checking the open circuit voltage over time. However, detection of these failure modes while the battery is in service is more difficult. The more critical the battery is to the safety of the aircraft, the more important it becomes to detect battery faults accurately. A number of on-board detection schemes have been developed for critical applications, mainly for military aircraft [Vutetakis and Viswanathan, 1995].

10.3.11 Disposal

Lead, the major constituent of the lead-acid battery, is a toxic (poisonous) chemical. As long as the lead remains inside the battery container, no health hazard exists. Improper disposal of spent batteries can result in exposure to lead, however. Environmental regulations in the U.S. and abroad prohibit the disposal of lead-acid batteries in landfills or incinerators. Fortunately, an infrastructure exists for recycling the lead from lead-acid batteries. The same processes used to recycle automotive batteries are used to recycle aircraft batteries. Federal, state, and local regulations should be followed for proper disposal procedures.

10.4 Nickel-Cadmium Batteries

10.4.1 Theory of Operation

The chemical reactions that occur in a nickel-cadmium battery are represented by the following equations:

$$\text{Positive electrode: } 2NiOOH + 2H_2O + 2e^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} 2Ni(OH)_2 + 2(OH)^- \qquad (6)$$

$$\text{Negative electrode: } Cd + 2(OH)^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} Cd(OH)_2 + 2e^- \qquad (7)$$

$$\text{Overall cell reaction: } 2NiOOH + Cd + 2H_2O \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} 2Ni(OH)_2 + Cd(OH)_2 \qquad (8)$$

There are two basic cell types: vented and recombinant. Vented cells have a flooded electrolyte, and the hydrogen and oxygen gases generated during charging are vented from the cell container. Recombinant cells have a starved electrolyte, and the oxygen generated from the positive electrode during charging diffuses to the negative electrode where it recombines to form cadmium hydroxide by the following reaction:

$$Cd + H_2O + 1/2O_2 \longrightarrow Cd(OH)_2 \qquad (9)$$

The recombination reaction suppresses hydrogen evolution at the negative electrode, thereby allowing the cell to be sealed. Unlike valve-regulated lead-acid cells, recombinant nickel-cadmium cells are sealed with a high-pressure vent that releases only during abusive conditions. Thus, these cells remain sealed under normal charging conditions. However, provisions for gas escape must still be provided when designing battery cases since abnormal conditions may be encountered periodically (e.g., in the event of a charger failure that causes an overcurrent condition).

10.4.2 Cell Construction

The construction of nickel-cadmium cells varies significantly, depending on the manufacturer. In general, cells feature alternating positive and negative plates with separator layers interleaved between them, a potassium hydroxide (KOH) electrolyte of approximately 31% concentration by weight (specific gravity 1.30), and a prismatic cell container with the cell terminals extending through the cover. The positive plate is impregnated with nickel hydroxide and the negative plate is impregnated with cadmium hydroxide. The plates differ according to manufacturer with respect to the type of the substrate, type of plaque, impregnation process, formation process, and termination technique. The most common plate structure is made of nickel powder sintered onto a substrate of perforated nickel foil or woven screens. At least one manufacturer (ACME) uses nickel-coated polymeric fibers to form the plate structure. Cell containers typically are made of nylon, polyamide, or steel. One main difference between vented cells and sealed (recombinant) cells is the type of separator. Vented cells use a gas barrier layer to prevent gases from diffusing between adjacent plates. Recombinant cells feature a porous separator system that permits gas diffusion between plates.

10.4.3 Battery Construction

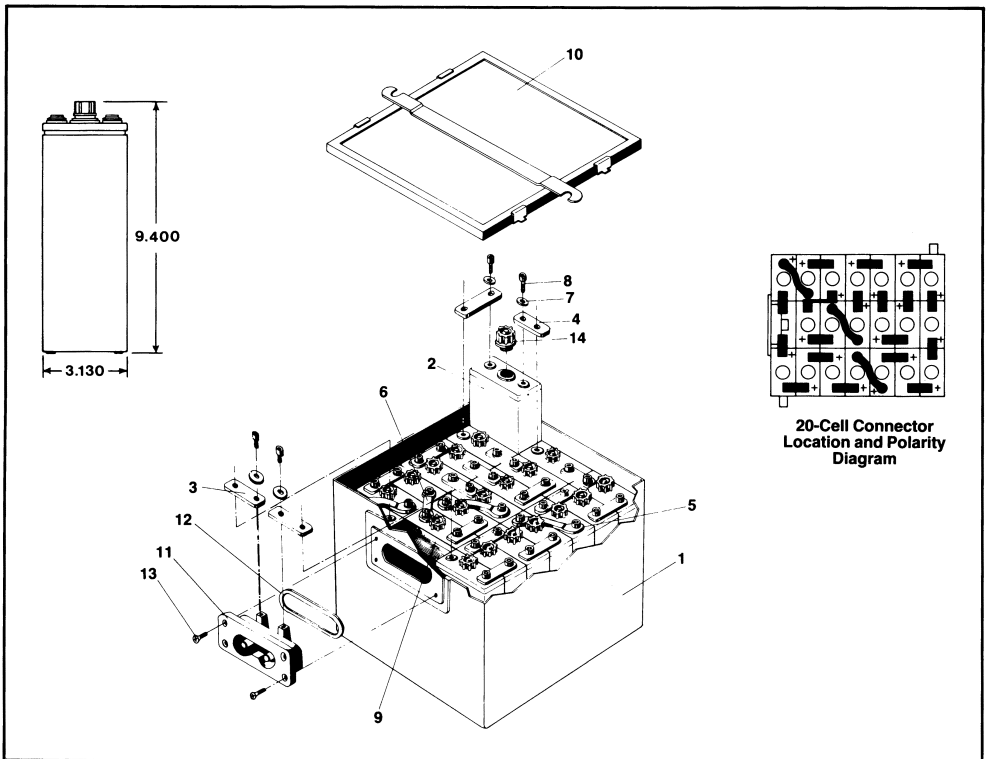
Nickel-cadmium aircraft batteries generally consist of a steel case containing identical, individual cells connected in series. The number of cells depends on the particular application, but generally 19 or 20 cells are used. The end cells of the series are connected to the battery receptacle located on the outside of the case. The receptacle is usually a two-pin, quick disconnect type; both Cannon and Elcon styles commonly are used. Cases are vented by means of vent tubes or louvers to allow escape of gases produced during overcharge. Some battery designs have provisions for forced air cooling, particularly for engine start applications. Thermostatically controlled heating pads sometimes are employed on the inside or outside of the battery case to improve low-temperature performance. Power for energizing the heaters normally is provided by the aircraft's AC or DC bus. Temperature sensors often are included inside the case to allow regulation of the charging voltage. In addition, many batteries are equipped with a thermal switch that protects the battery from overheating if a fault develops or if battery is exposed to excessively high temperatures. A typical aircraft battery assembly is shown in Figure 10.5.

10.4.4 Discharge Performance

Typical discharge performance data for VNC aircraft batteries are illustrated in Figures 10.6 and 10.7. Discharge characteristics of SNC batteries are similar to VNC batteries. Figure 10.4 shows the effect of temperature on discharge capacity at the C-rate. Compared with lead-acid batteries, nickel-cadmium batteries tend to have more available capacity at low temperature, but less available capacity at high temperature. Manufacturers' data should be consulted for current information on specific batteries of interest.

10.4.5 Charge Methods

A variety of methods are employed to charge nickel-cadmium aircraft batteries. The key requirement is to strike an optimum balance between overcharging and undercharging, while achieving full charge in the required time frame. Overcharging results in excessive water loss (vented cells) or heating (sealed cells). Undercharging results in capacity fading. Some overcharge is necessary, however, to overcome coulombic inefficiencies associated with the electrochemical reactions. In practice, recharge percentages on the aircraft generally range between 105 and 120%.



Item	Description	Quantity	Item	Description	Quantity
1	Can Assembly	1	8	Socket Head Cap Screw	42
2	Cell Assembly	20	9	Spacer	1
3	Connector	12	10	Cover Assembly	1
4	Connector	5	11	Receptacle Assembly	1
5	Connector	3	12	Rectangular Ring	1
6	Connector	1	13	Phillips Head Screw	4
7	Belleville Spring	42	14	Filler Cap and Vent Assembly	20

FIGURE 10.5 Assembly drawing of a nickel-cadmium aircraft battery.

For vented-cell batteries, common methods of charging include constant potential, constant current, or pulse current. Constant potential charging is the oldest method and normally is accomplished by floating a 19-cell battery on a 28-V DC bus. The constant current method requires a dedicated charger and typically uses a 0.5 to 1.5 C-rate charging current. Charge termination is accomplished using a temperature-compensated voltage cutoff (VCO). The VCO temperature coefficient is typically (−) 4mV/°C. In some cases, two constant current steps are used, the first step at a higher rate (e.g., C-rate), and the second step at a lower rate (e.g., 1/3 to 1/5 of the C-rate). This method is more complicated, but results in less gassing and electrolyte spewage during overcharge. Pulse current methods are similar to the constant current methods, except the charging current is pulsed rather that constant.

For sealed-cell batteries, only constant current or pulse current methods should be used. Constant potential charging can cause excessive heating, resulting in thermal runaway. Special attention must be given to the charge termination technique in sealed-cell batteries, because the voltage profile is relatively flat as the battery becomess fully charged. For example, it may be necessary to rely on the battery's temperature rise rather than voltage rise as the signal for charge termination.

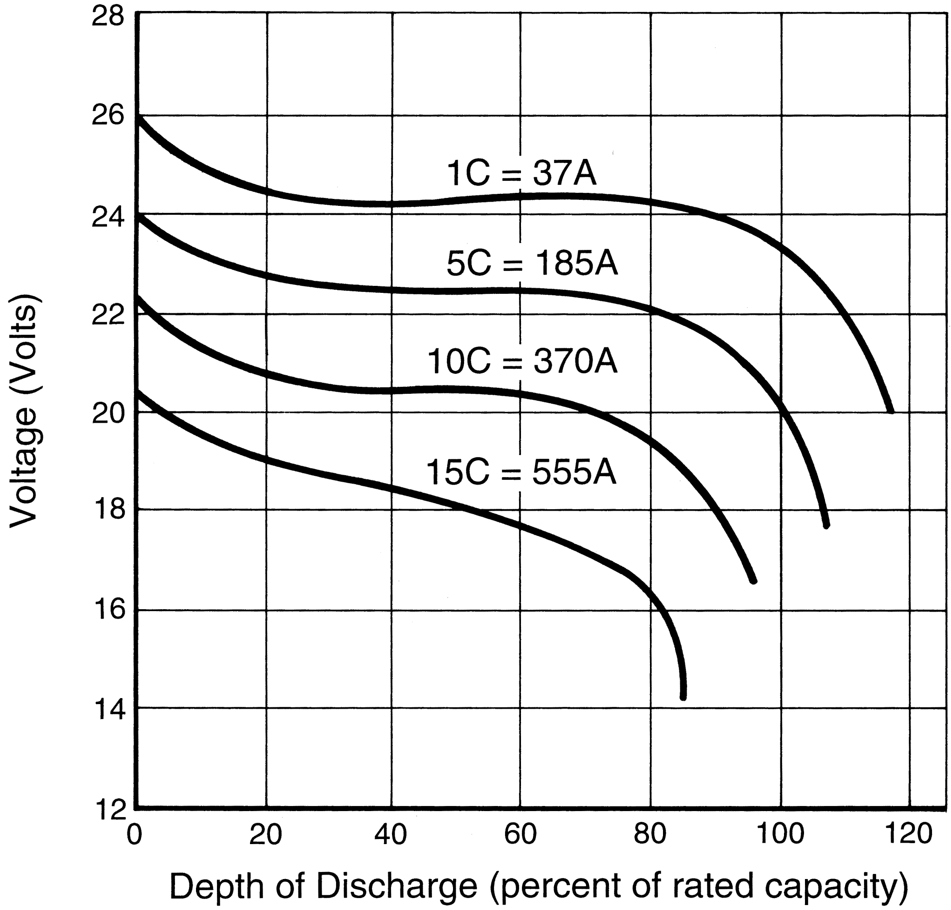


FIGURE 10.6 Discharge curves at 25°C for a 24 V/37 Ah VNC aircraft battery.

10.4.6 Temperature Effects and Limitations

Nickel-cadmium batteries, like lead-acid batteries, normally are rated at room temperature (25°C) and operate best around this temperature. Exposure to low ambient temperatures results in performance decline, and exposure to high ambient temperatures results in shortened life.

The lower temperature limit is dictated by the freezing point of the electrolyte. Most cells are filled with an electrolyte concentration of 31% KOH, which freezes at −66°C. Lower concentrations will freeze at higher temperatures, as shown in Table 10.3. The KOH concentration may become diluted over time as a result of spillage or carbonization (reacting with atmospheric carbon dioxide), so the freezing point of a battery in service may not be as low as expected. As in the case of dilute acid electrolytes, slush ice will form well before the electrolyte freezes solid. For practical purposes, a lower operating temperature limit of −40°C often is quoted.

The upper temperature limit is generally in the range of 50 to 60°C; significant capacity loss occurs when batteries are operated (i.e., repeated charge/discharge cycles) above this temperature range. The battery capacity often is recoverable, however, when the battery is cooled to room temperature and subjected to several deep discharge cycles.

10.4.7 Service Life

The service life of a nickel-cadmium aircraft battery depends on many factors, including the type of use it experiences (e.g., rate, frequency, and depth of discharge), environmental conditions (e.g., temperature

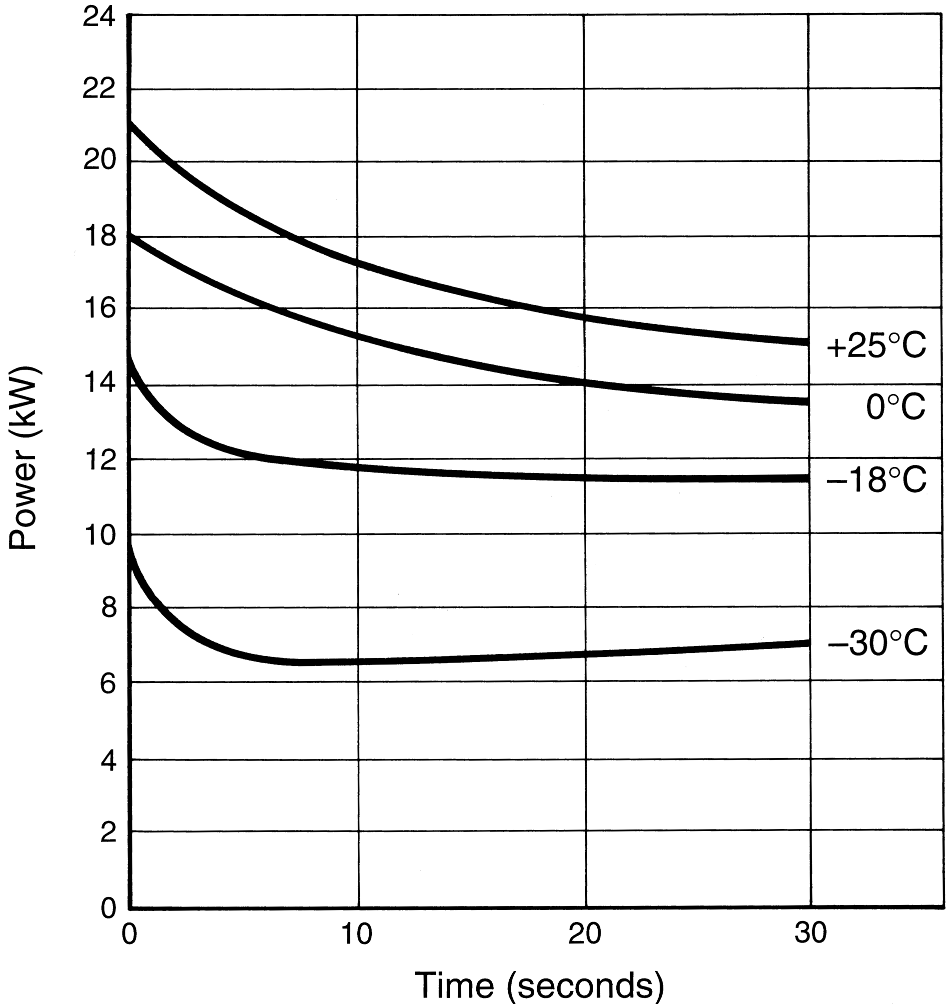


FIGURE 10.7 Maximum power curves (12 V discharge) for a 24 V/37 Ah VNC aircraft battery.

TABLE 10.3 Freezing Points of KOH-Water Mixtures

Concentration (Weight %)	Specific Gravity at 15°C	Freezing Point (°C)	Freezing Point (°F)
0	1.000	0	+32
5	1.045	−3	+27
10	1.092	−8	+18
15	1.140	−15	+5
20	1.118	−24	−11
25	1.239	−38	−36
30	1.290	−59	−74
31	1.300	−66	−87
35	1.344	−50	−58

and vibration), charging method, and the care with which it is maintained and reconditioned. Thus, it is difficult to generalize the service life that can be expected. All things being equal, the service life of a nickel-cadmium battery is inherently longer than that of a lead-acid battery. Representative cycle life data for an SNC battery are listed in Table 10.4.

TABLE 10.4 Cycle Life Data for SNC Aircraft Batteries

Depth of Discharge (% of Rated Capacity)	Number of Cycles to End of Life
30	7500
50	4500
60	3000
80	1500
100	1000

Source: ACME Electric Corporation.

10.4.8 Storage Characteristics

Nickel-cadmium batteries can be stored in any state of charge and over a broad temperature range (i.e., −65 to 60°C). For maximum shelf life, however, it is best to store batteries between 0 and 30°C. Vented-cell batteries normally are stored with the terminals shorted together. Shorting of sealed-cell batteries during storage is not recommended, however, since it may cause cell venting and/or cell reversal.

When left on open circuit during periods of non-operation, nickel-cadmium batteries will self-discharge at a relatively fast rate. As a rule of thumb, the self-discharge rate of sealed cells is approximately 1%/day at 20°C (when averaged over 30 days), and the rate increases by 1%/day for every 10°C rise in temperature (e.g., 2%/day at 30°C, 3%/day at 40°C, etc.). The self-discharge rate is somewhat less for vented cells. The capacity lost by self-discharge usually is recoverable when charged in the normal fashion.

10.4.9 Maintenance Requirements

Routine maintenance of nickel-cadmium aircraft batteries is required to assure airworthiness and to maximize service life. Maintenance intervals for vented-cell batteries in military aircraft are typically 60 to 120 days. Maintenance intervals for commercial aircraft can be as low as 100 and as high as 1000 flight hours, depending on the operating conditions. Maintenance procedures include capacity checks, cell equalization (deep discharge followed by shorting cell terminals for at least 8 h), isolating and replacing faulty cells (only if permitted; this practice generally is not recommended), cleaning to remove corrosion and carbonate build-up, and electrolyte adjustment.

For sealed-cell batteries, maintenance requirements are much less demanding. Electrolyte adjustment is unnecessary, and the extent of corrosion is greatly reduced. However, some means of assuring airworthiness is still necessary, such as periodic capacity measurement. Manufacturers' recommendations should be followed for specific batteries of interest.

10.4.10 Failure Modes and Fault Detection

The predominant failure modes of nickel-cadmium cells are summarized as follows:

- Shorts caused by cadmium migration through the separator, swelling of the positive electrode, degradation of the separator, or mechanical defects protruding from the electrode. Manifested by inability of the battery to hold a charge (soft shorts) or dead cells (hard shorts).
- Water loss and resulting cell dry-out due to leaking seal, repeated cell reversal, or excessive overcharge (this mode applies to sealed cells or to vented cells that are improperly maintained). Manifested by low capacity and/or inability to hold voltage under load.
- Loss of negative (cadmium) electrode capacity due to passivation or active material degradation. Manifested by low capacity and/or inability to hold voltage under load. Usually reversible by deep discharge followed by shorting cell terminals, or by "reflex"charging (pulse charging with momentary discharge between pulses).
- Loss of positive (nickel) electrode capacity due to swelling or active material degradation. Manifested by low capacity that is nonrestorable.

As discussed under lead-acid batteries, detection of these failure modes is relatively straightforward if the battery can be removed from the aircraft. For example, the battery capacity and load capability can be directly measured and compared against pass/fail criteria. The occurrence of soft shorts (i.e., a high impedance short between adjacent plates) is more difficult to detect, but often can be identified by monitoring the end-of-charge voltage of individual cells.

Detection of these failure modes while the battery is in service is more difficult. As in the case of lead-acid batteries, a number of on-board detection schemes have been developed for critical applications [Vutetakis and Viswanathan, 1995]. The more critical the battery is to the safety of the aircraft, the more important it becomes to detect battery faults accurately.

10.4.11 Disposal

Proper disposal of nickel-cadmium batteries is essential because cadmium is a toxic (carcinogenic) chemical. In the U.S. and abroad, spent nickel-cadmium batteries are considered to be hazardous waste, and their disposal is strictly regulated. Several metallurgical processes have been developed for reclaiming and recycling the nickel and cadmium from nickel-cadmium batteries. These processes can be used for both vented and sealed cells. Federal, state, and local regulations should be followed for proper disposal procedures.

10.5 Applications

Designing a battery for a new aircraft application or for retrofit requires a careful systems engineering approach. To function well, the battery must be interfaced carefully with the aircraft's electrical system. The battery's reliability and maintainability depends heavily on the type of charging system to which it is connected; there is a fine line between undercharging and overcharging the battery. Many airframe manufacturers have realized that it is better to prepare specifications for a "battery system" rather than having separate specifications for the battery and the charger. This approach assures that the charging profile is tuned correctly to the specific characteristics of the battery and to the aircraft's operational requirements.

10.5.1 Commercial Aircraft

A listing of commercial aircraft batteries available from various manufacturers is given in Table 10.5. Sizes range from 12 V/6.5 Ah to 24 V/65 Ah. The table includes VLA, SLA, and VNC type batteries. SNC batteries are not included, but are available on a limited basis from several manufacturers (ACME, SAFT, and Eagle-Picher).

In general, the aircraft battery must be sized to provide sufficient emergency power to support flight essential loads in the event of failure of the primary power system. FAA regulations impose a minimum emergency power requirement of 30 min on all commercial airplanes. Some airlines impose a longer emergency requirement, such as 40 or 60 min due to frequent bad weather on their routes or for other reasons. The emergency requirement for Extended Twin Operation (ETOPS) imposed on two-engine aircraft operating over water is a full 90 min, although 60 min is allowed with operating restrictions. The specified emergency power requirement may be satisfied by batteries or other backup power sources, such as a ram air turbine. If a ram air turbine is used, a battery still is required for transient fill-in. Specific requirements pertaining to aircraft batteries can be found in the Federal Aviation Regulations (FAR), Sections 25.1309, 25.1333, 25.1351, and 25.1353. FAA Advisory Circular No. 25.1333-1 describes specific methods to achieve compliance with applicable FAR sections. For international applications, Civil Aviation Authority (CAA) and Joint Airworthiness Authority (JAA) regulations should be consulted for additional requirements.

When used for APU or engine starting, the battery must be sized to deliver short bursts of high power, as opposed to the lower rates required for emergency loads. APU start requirements on large commercial aircraft can be particularly demanding; for instance, the APU used on the Boeing 757 and 767 airplanes has a peak current requirement of 1200 A [Gross, 1991]. The load on the battery starts out very high to

TABLE 10.5 Commercial Aircraft Batteries

RATING[a]	CONCORDE	CONCORDE SLA	TELEDYNE VLA	TELEDYNE SLA	HAWKER SLA	MARATHON VNC	SAFT VNC
12V/6.5Ah							615
12V/10Ah					SBS-15		
12V/15Ah				G-30s			10.15
12V/18Ah	CB-25	RG-25	G-25		SBS-30		
			G-25M				
12V/23Ah	CB-35	RG-35	G-35	G-35S			
	CB-35M		G-35M				
12V/25Ah					SBS-40		
12V/37Ah					SBS-60		
12V/65Ah	CB12-88		G-88				
13.2V/36Ah						CA-138	40153
						SP-138	40253
13.2V/40Ah						CA-13	40152
						CA-13-1	
						CA-130	
13.2V/42Ah							40353
22.8V/3Ah						CA-13	19V03KHB
						CA-125	
						MA-300H	
22.8V/5.5Ah						CA-51	
						CA-53	
						CA-54	
						MA-500H	
22.8V/6.5Ah							605
22.8V/7Ah							19V07L
22.8V/12Ah							1201
							12101
22.8V/13Ah						CA-7	
						CA-10N	
						CA-515A/B	
						CA-101	
						CA-103	
						CA-106	
						CA-154	

22.8V/14Ah							1277
							1277-1
22.8V/15Ah							12277
22.8V/20Ah						CA-20H	
						CA-21H	
22.8V/22Ah							23175
22.8V/23Ah							19V023KHP
							2353-1
22.8V/24Ah						CA-4	
						CA-9	
						MA-11	
						CA-24A/B	
						CA-27	
						CA-272-7	
						KCA-727	
						CA-737	
22.8V/40Ah						CA-5	
						KA-5h	
						MA-5	
						CA-747	
22.8V/60Ah						CA-88A/B	
22.8V/65Ah						MA-2-1	
24V/3Ah						MA-300	20V03KHB
24V/5Ah					9750B0818		
24V/8Ah	CB24-9		G-240				
	CB24-9M		G-241				
24V/10Ah	CB24-11	RG-24-11M	G-242	G-242S	9750R0817		
	CB24-11M		G-243	G-243s	9750R0819		
			GE-54C		9750R0824		
			GE-54E		9750G082		
24V/14Ah		RG-400E					
24V/14Ah	CB24-40E		G-640C			CA-154-5	
			G-640E				

(continued)

TABLE 10.5 Commercial Aircraft Batteries (Continued)

RATING[a]	CONCORDE	CONCORDE SLA	TELEDYNE VLA	TELEDYNE SLA	HAWKER SLA	MARATHON VNC	SAFT VNC
24V/15Ah							2.10.15
							1656
							1656-1
							16156
							16256
							16356
24V/16Ah							2.10.16.1
							1600
							1606
							1666-1
							16150
24V/17Ah						CA-170A	1658
						SP-170A	1756
						CA-176	
						SP-176	
						CA-1700	
						SP-1700	
						CA-1717	
						CA-1735	
						SP-1735	
						CA-1751	
						SP-1751	
						CA-1752	
						CA-1753	
						SP-1753	
24V/18Ah			G-244		9750D0730		
			G-245		9750D0734		
			G-641		9750D0738		
					9750D0740		
					9750D0741		
					9750D0742		
					9750D0744		
					9750D0745		
					9750S0746		
					9750S0775		

24V/19Ah	CB24-20	G-246		
		G-247		
24V/20Ah			CA-20H-20	
			CA-21H-20	
			KTCA-21H-20	
24V/22Ah	CB24-3151	GE-51C		2026
	CB24-3151-1	GE-51E		2376
	CB24-3151E			2376-1
				2376-2
				2376-5
				20126
				23176
				23186
				23376
				23476
				23576
				23676
24V/23Ah				2371
				2371-1
				2506
				2506-1
				23180
				23390
				23396
				23491
				25106
				25106-2
24V/24Ah			CA-4-20	
			CA-9-20	
			CA-27-20	
			CA-91-20	
			TCA-94A	
			CA-727-9	
			CA-727-20	

(continued)

TABLE 10.5 Commercial Aircraft Batteries (Continued)

RATING[a]	CONCORDE	CONCORDE SLA	TELEDYNE VLA	TELEDYNE SLA	HAWKER SLA	MARATHON VNC	SAFT VNC
						KCA-727-20	
						CA-900	
						SP-900	
						TSP-900AT	
						CA-910	
						SP-910	
						CA-930A	
						SP-930A	
24V/25Ah	CB24-39C			G-639ES	9750T0639		
	CB24-39E				9750E0640		
					9750E0647		
					9750E0650		
24V/25Ah					9750E0658		2500
					9750E0660		25201
					9750Y0662		
					9750T0663		
					9750T0667		
					9750E0750		
					9750E0751		
24V/26Ah		RG-390E	G-639C				2378
			G-639E				23178
24V/27Ah							2778
							2778-2
							2778-4
24V/28Ah						SP-280	
24V/31Ah	CB24-3150		GE-50C				
	CB24-3150-1		GE-50E				
	CB24-3150E						
24/35Ah				G-6381ES			2.10.35.A
24V/36Ah					9752D0736	CA-401	4006A
					9752H0754	SP-401	4006A-1
						CA-538	40100A
						TCA-380	40206
						TSP-380	40306

					4076
					4076-1
					4076-2
					4076-5
					4076-9
					40176
					40176-4
					40176-7
					40376
					40576
					40676
					40876
24V/37Ah		G-638E	9750F0530		4079
		G-638C	9750F0531		A4079
			9750F0532		40109-1
			9750F0539		40209
			9750F0540		A40209
			9750V0546		
24V/40Ah	RG-380E/40A			CA-5-20	400A1
	RG-380E/40B			CA-5H-20	4000A1-1
				MA-5-20	4579
				CA-14	40776
				CA-16	401076
				CA-16L	401176
				CA-16L-2	40100-1
24V/40Ah				CA-376	4050A1
				SP-376	4050A1-1
				CA-400	4071
				SP-400	4071-1
				TCA-406	4071-2
				CA-420	4080
				SP-420	
				SP-420L	
				CA-430	
				CA-440	
				SP-440	
				KTCA-747	

(continued)

TABLE 10.5 Commercial Aircraft Batteries (Continued)

RATING[a]	CONCORDE	CONCORDE SLA	TELEDYNE VLA	TELEDYNE SLA	HAWKER SLA	MARATHON VNC	SAFT VNC
24V/43Ah			G-63381C				4078
			G-6381E				4078-4
							4078-7
							40208
							40208-1
							40208-2
							40378
24V/44Ah		RG-380E/40					
24V/45Ah	CB24-380C						
	CB24-380E						
24V/48Ah	CB24-382E						
24V/50Ah							21931
							21932
24V/65Ah						MA-2	
26.4V/7Ah							22V07L
26.4V/13Ah						CA-121	
26.4V/50Ah							5103

[a] Voltage rating is based on 1.2 V per cell for nickel-cadmium and 2.0 V per cell for lead-acid. Capacity rating is based on the one-hour rate.

deliver the in-rush current to the motor, then falls rapidly as the motor develops back electromotive force (EMF). Within 30 to 60 s, the load drops to zero as the APU ignites and the starter cutoff point is reached. The worst-case condition is starting at altitude with a cold APU and a cold battery; normally, a lower temperature limit of -18°C is used as a design point. A rigorous design methodology for optimizing aircraft starter batteries was developed by Evjen and Miller [1971].

When nickel-cadmium batteries are used for APU or engine starting applications, FAA regulations require the battery to be protected against overheating. Suitable means must be provided to sense the battery temperature and to disconnect the battery from the charging source if the battery overheats. This requirement originated in response to numerous instances of battery thermal runaway, which usually occurred when 19-cell batteries were charged from the 28-volt DC bus. Most instances of thermal runaway were caused by degradation of the cellophane gas barrier, thus allowing gas recombination and resultant cell heating during charging. Modern separator materials (e.g., Celgard) have greatly reduced the occurrence of thermal runaway as a failure mode of nickel-cadmium batteries, but the possibility still exists if the electrolyte level is not properly maintained.

10.5.2 Military Aircraft

A listing of commonly used military aircraft batteries is provided in Table 10.6. This listing includes only those batteries that have been assigned a military part number based on an approved military specification; nonstandard batteries are not included. Detailed characteristics and performance capabilities can be found by referring to the applicable military specifications. A number of nonstandard battery designs have been proliferated in the military due to the unique form, fit, and/or functional requirements of certain aircraft. Specifications for these batteries normally are obtainable only from the aircraft manufacturer. Specific examples of battery systems used in present-day military aircraft were recently described by Vutetakis [1994].

Defining Terms

Ampere-hour capacity: The quantity of stored electrical energy, measured in ampere-hours, that the battery can deliver from its completely charged state to its discharged state. The dischargeable capacity depends on the rate at which the battery is discharged; at higher discharge rates the available capacity is reduced.

C-rate: The discharge rate, in amperes, at which a battery can deliver 1 h of capacity to a fixed voltage endpoint (typically 18 or 20 V for a 24-V battery). Fractions or multiples of the C-rate also are used. C/2 refers to the rate at which a battery will discharge its capacity in 2 h; 2C is twice the C-rate or that rate at which the battery will discharge its capacity in 0.5 h. This rating system helps to compare the performance of different sizes of cells.

CCA: The numerical value of the current, in amperes, that a fully charged lead-acid battery can deliver at −18°C (0°F) for 30 s to a voltage of 1.2 V per cell (i.e., 14.4 V for a 24-V battery). In some cases, 60 s is used instead of 30 s. CCA stands for cold cranking amperes.

Electrolyte: An ionically conductive, liquid medium that allows ions to flow between the positive and negative plates of a cell. In lead-acid cells, the electrolyte is a mixture of sulfuric acid (H_2SO_4) and deionized water. In nickel-cadmium cells, the electrolyte is a mixture of potassium hydroxide (KOH) dissolved in deionized water.

Imp: The numerical value of the current, in amperes, delivered after 15 s during a constant voltage discharge of 0.6 V per cell (i.e., at 12 V for a 24-V battery). The Imp rating normally is based on a battery temperature of 23°C (75°F), but manufacturers generally can supply Imp data at lower temperatures as well.

Monobloc: A group of two or more cells connected in series and housed in a one-piece enclosure with suitable dividing walls between cell compartments. Typical monoblocs come in 6-V, 12-V, or 24-v configurations. Monoblocs are commonly used in lead-acid batteries, but rarely used in nickel-cadmium aircraft batteries.

TABLE 10.6 Military Aircraft Batteries

Military Part No	Type	Rating[a] (Ah)	Max. Wt. (lb)	Applications	Notes
				MIL-B-8565 Series	
D8565/1-1	SNC	2.0 (26 V)	8.6	AV-8A/C, CH-53E, MH-53E	Contains integral charger.
D8565/2-1	VNC	30	88.0	OV-10D	Superceded by M81757/12-1.
D8565/3-3	SLA	15	47.4	V-22(EMD)	MS3509 connector.
D8565/4-1	SLA	7.5	26.0	F/A-18A/B/C/D, CH-46D/E, HH-46A, UH-46A/D, F-117A	MS27466T17B6S connector.
D8565/5-1		30	80.2	C-1A, SP-2H, A-3B, KA-3B, RA-3B, ERA-3B, NRA-3B, UA-3B, P-3A/B/C, EP-3A/B/E, RP-3A, VP-3A, AC-130A/H/U, C-130A/B/E/F/H, DC-130A, EC-130EH/G/Q, HC-130H/N/P, KC-130F/R/T, LC-130F/H/R, LC-130F/H/R, MC-130E/H, NC-130A/B/H, WC-130E/H, C-18A/B, EC-18B/D, C-137B/C, EC-137D, E-8A, TS-2A, US-2A/B, T-28B/C, QT-33A, MH-53J, MH-60G	Equivalent to D8565/5-2, except uses MS3509 connector.
D8565/5-2	SLA	30	80.2	Same as D8565/5-1 (for aircraft equipped with Cannon style mating connector)	Equivalent to D8565/5-1, except uses Cannon connector.
D8565/6-1	SLA	1.5	6.4	V-22A, CV-22A, CH-47E	MS27466715B5S connector.
D8565/7-1	SLA	24	63.9	AV-8B, TAV-8B, VH-60A, V-22A, CV-22A	MS3509 connector.
D8565/7-2	SLA	24	63.9	Same as D8565/7-1	Replacement for D8565/7-1 with higher rate capability.
D8565/8-1	SLA	15	43.0	T-45A	Cannon connector.
D8565/9-1	SLA	24	63.0	T-34B/C, U-6A	MS3509 connector.
D8565/9-2	SLA	24	63.0	None identified	Cannon connector.
D8565/10-1	VNC	35	85.0	AH-1W	MS3509 connector. Equipped with temperature sensor.
D8565/11-1	SLA	10	34.8	F-4D/E/G, C-141B, MH-60E, NC-141A, YF-22A	Equivalent to D8565/11-2, except uses MS3509 connector.
D8565/11-2	SLA	10	34.8	None identified	Equivalent to D8565/11-1, except uses Cannon connector.
D8565/12-1	SLA	35	90.0	None identified	MS3509 connector.
D8565/13-1	SLA	10	31.0	Carousel IV, LTN-72 Inertial Navigation Systems (INS)	ARINC 1/2 ATR case.
D8565/14-1	SLA	15	45.2	F-18E/F	D38999/24YG11SN connector
D8565/15-1	SLA	35	90.0	C/KC-135 series	MS3509 connector.
				MIL-B-8565 Specials	
MS3319-1	VNC	0.75	3.5	HH-2D, SH-2D/F	MS3106-12S-3P connector.
MS3337-2	SNC	0.40	4.0	F-4s	Obsolete.

MS3346-1	VNC	2.5	10.0	A-7D/E, TA-7C	Obsolete.
MS3487-1	VNC	18	50.0	AH-1G	Equivalent to BB-649A/A.
MS17334-2	SNC	0.33	3.5	E-1B, EA-6B, US-2D	MS3106R14S-7P connector.
				MIL-B-83769 Series	
M83769/1-1	VLA	31	80.0	Same as D8565/5-1 (for aircraft equipped with Cannon style mating connector)	Supercedes AN3150. Equivalent to BB-638/U. Interchangeable with D8565/5-2 (Cannon connector).
M83769/2-1	VLA	18	56.0	AC-130H/U, NU-1B, U-6A	Supercedes AN3151. Equivalent to BB-639/U. Interchangeable with D8565/9-2 (Canon connector).
M83769/3-1	VLA	8.4	34.0	C-141B, NC-141A	Supercedes AN3154. Equivalent to BB-640/U. Interchangeable with D8565/11-2 (Cannon connector).
M83769/4-1	VLA	18	55.0	T34B/C	Supercedes MS18045-41. Interchangeable with D8565/9-1 (MS3509 connector).
M83769/5-1	VLA	31	80.0	Same as D8565/5-1	Supercedes MS18045-42. Interchangeable with D8565/5-1 (MS3509 connector).
M83769/6-1	VLA	31	80.0	Same as D8565/5-1 (for aircraft equipped with Cannon style mating connector)	For ground use only. Equivalent to M83769/1-1 when filler caps are replaced with aerobatic vent plugs. Equipped with Cannon connector.
M83769/7-1	VLA	54(12V)	80.0	C-117D, C-118B, VC-118, C-131F, NC-131H, T-33B	Supercedes MS90379-1. Equipped with threaded terminals.
				MIL-B-81757 Series (Tri-Service)	
M81757/7-2	VNC	10	34.0	CH-46A/D/E/F, HH-46A, UH-46A/D, U-8D/F	Replaceable cells. Superceds MS24496-1 and MS24496-2.
M81757/7-3	VNC	10	34.0	Same as M81757/7-2	Nonreplaceable cells. Supercedes MS18045-44, MS18045-48 and MS90221-66W.
M81757/8-4	VNC	20	55.0	C-2A, T-2C, T-39A/B/D, OV-10A	Replaceable cells. Supercedes MS24497-3, MS24497-5, and M81757/8-2.

(continued)

TABLE 10.6 Military Aircraft Batteries (Continued)

Military Part No	Type	Rating[a] (Ah)	Max. Wt. (lb)	Applications	Notes
M81757/8-5	VNC	20	55.0	Same as M81757/8-4	Nonreplaceable cells. Supercedes MS90365-1, MS90365-2, MS90321-68W, MS90321-77, MS90321-78W, MS18045-45, MS18048-49, and M81757/8-3.
M81757/9-2	VNC	30	80.0	CT-39A/E/G, NT-39A, TC-4C, HH-1K, TH-1L, UH-1E/H/L/N, AH-1J/T, LC-130F/R, OV-1B/C/D	Replaceable cells. Supercedes MS24498-1 and MS24498-2.
N81757/9-3	VNC	30	80.0	Same as M81757/9-2	Nonreplaceable cells. Supercedes MS18045-46, MS18045-50, MS90321-75W, MS90321-69W.
M81757/10-1	VNC	6(23V)	24.0	A-6E, EA-6A, KA-6D	Nonreplaceable cells. Supercedes MS90447-2 and MS90321-84W.
M81757/11-3	VNC	20	55.0	HH-2D, SH-2D/F/G, HH-3A/E, SH-3D/G/H, UH-3A, VH-3A	Nonreplaceable cells. Supercedes MS90377-1, MS90321-79W and M81757/11-1.
M81757/11-4	VNC	20	55.0	None identified	Nonreplaceable cells with temperatur sensor. Supercedes MS90377-1, MS90321-79W and M81757/11-2.
M81757/12-1	VNC	30	88.0	OV-10D	Nonreplaceable cells, air-cooled. Supercedes D8565/2-1.
M81757/12-2	VNC	30	88.0	C-2A (REPRO), OV-10D	nonreplaceable cells, air-cooled, with temperature sensor.
M81757/13-1	VNC	30	80.0	EA-3B, ERA-3B, UA-3B	Non replaceable cells. Supercedes MS18045-75.
				MIL-B-26220 Series (U.S. Air Force)	
MS24496-1	VNC	11(C/2)	34.0	F-111A/D/E/F/G, EF-111A, FB-111A	Superceded by M81757/7-2.
MS24496-2	VNC	11(C/2)	34.0	F-4D/E/G, NF-4C/D/E, NRF-4C, RF-4C, YF-4E	Superceded by M81757/7-2.
MS24497-3	VNC	22(C/2)	55.0	None identified	Superceded by M81757/8-2.
MS24497-4	VNC	22(C/2)	60.0	B-52H	Contains integral heater.
MS24497-5	VNC	22(C/2)	55.0	B-52G, C-135, EC-135, KC-135, NC-135, NKC-135, RC-135, TC-135, TC-135, WC-135, E-4B CH-3E, NA-37B, OA-37B, OV-10A	Superceded by M81757/8-2.

MS24498-1	VNC	34(C/2)	80.0	A-10A, C-20A, C-137A/B, EC-137D, OA-10A, T-37B, T-41A/B/C/D, HH-1H, UH-1N, CH-53A, MH-53J, NH-53A, TH-53A	Superceded by M81757/8-2.
MS24498-2	VNC	34(C/2)	80.0	None identified	Superceded by M81757/9-2.
MS27546	VNC	5	16.0	T-38A	Superceded by Marathon P/N 30030.
				BB-Series (U.S. Army)	
BB-432A/A	VNC	10	34.0	CH-47A/B/C, U-8F	Equivalent to M81757/7-2.
BB-432B/A	VNC	10	34.0	CH-47D	Equivalent to BB-432A/A, except includes a temperature sensor.
BB-433A/A	VNC	30	80.0	C-12C/D/F/L, OV-1D, EH-1H/X, UH-1H/V, RU-21A/B/C/H	Equivalent to M81757/9-2.
BB-434/A	VNC	20	55.0	CH-54	Equivalent to M81757/8-4.
BB-476/A	VNC	13	27.6	OH-58A/B/C	
BB-558/A	VNC	17	38.5	OH-58D	
BB-564/A	VNC	13	25.0	AH-64A	Superceded by BB-664/A.
BB-638/U	VLA	31	80.0	None identified	Equivalent to M83769/1-1.
BB-638A/U	VLA	31	80.0	None identified	Equivalent to M83769/6-1
BB-639/U	VLA	18	56.0	None identified	Equivalent to M83769/2-1.
BB-640/U	VLA	8.4	34.0	None identified	Equivalent to M83769/3-1.
BB-649A/A	VNC	18	50.0	AH-1E/F/P/S	Equivalent to MS3487-1.
BB-664/A	VNC	13	27.0	A-64A	
BB-678A/A	VNC	13	24.8	OH-6A	
BB-693A/U	VNC	30	83.0	Vulcan	
BB-708/U	VNC	5.5	15.0	OV-1D (Mission Gear Equipment)	
BB-716/A	VNC	5.5	17.5	EH-60A, HH-60H/J, SH-60B/F, UH-60A	

[a]Capacity rating is based on the one-hour rate unless otherwise noted. Voltage rating is 24 V unless otherwise noted.

Negative electrode: The electrode from which electrons flow when the battery is discharging into an external circuit. Reactants are electrochemically oxidized at the negative electrode. In the lead-acid cell, the negative electrode contains spongy lead and lead sulfate ($PbSO_4$) as the active materials. In the nickel-cadmium cell, the negative electrode contains cadmium and cadmium hydroxide ($Cd(OH)_2$) as the active materials.

Nominal voltage: The characteristic operating voltage of a cell or battery. The nominal voltage is 2.0 V for lead-acid cells and 1.2 V for nickel-cadmium cells. These voltage levels represent the approximate cell voltage during discharge at the C-rate under room-temperature conditions. The actual discharge voltage depends on the state-of-charge, state-of-health, discharge time, rate, and temperature.

Positive electrode: The electrode to which electrons flow when the battery is discharging into an external circuit. Reactants are electrochemically reduced at the positive electrode. In the lead-acid cell, the positive electrode contains lead dioxide (PbO_2) and lead sulfate ($PbSO_4$) as the active materials. In the nickel-cadmium cell, the positive electrode contains nickel oxyhydroxide (NiOOH) and nickel hydroxide ($Ni(OH)_2$) as the active materials.

Separator: An electrically insulating material that is used to prevent metallic contact between the positive and negative plates in a cell, but permits the flow of ions between the plates. In flooded cells, the separator includes a gas barrier to prevent gas diffusion and recombination of oxygen. In sealed cells, the separator is intended to allow gas diffusion to promote high recombination efficiency.

State-of-charge: The available capacity of a battery divided by the capacity available when fully charged, normally expressed on a percentage basis. Sometimes referred to as "true state-of-charge."

State-of-health: The available capacity of a fully charged battery divided by the rated capacity of the battery, normally expressed on a percentage basis. Sometimes referred to as "apparent state-of-charge." Can also be used in a more qualitative sense to indicate the general condition of the battery.

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Further Information

The *Handbook of Batteries and Fuel Cells* by David Linden contains extensive technical data on all battery types, and several chapters are devoted to lead-acid and nickel-cadmium batteries. The second edition of this handbook was published recently (McGraw-Hill, 1995). Engineering handbooks for nickel-cadmium batteries have been published by several battery manufacturers, including General Electric, Gates Energy (now Hawker Energy), and SAFT. An SAE specification for vented nickel-cadmium aircraft batteries, Aerospace Standard AS-8033, was published in 1981 and reaffirmed in 1988.

The following technical manuals are published by the Department of Defense and provide detailed operation and servicing instructions for aircraft batteries:

- NAVAIR 17-15BAD-1, Naval Aircraft and Naval Aircraft Support Equipment Storage Batteries. Request for this document should be referred to Commanding Officer, Naval Air Technical Services Facility, 700 Robbins Avenue, Philadelphia, PA 19111.
- T.O. 8D2-3-1, Aircraft Nickel-Cadmium Storage Batteries. Request for this document should be referred to Sacramento ALC/TILBE, McClellan AFB, CA 95652-5990.
- T.O. 8D2-1-31, Aircraft Storage Batteries (Lead-Acid Batteries). Request for this document should be referred to Sacramento ALC/TILBE, McClellan AFB, CA 95652-5990.
- T.M. 11-6140-203-23, Maintenance Manual for Aircraft Nickel-Cadmium Batteries. Requests for this document should be referred to CECOM, ATTN: AMSEL-LC-LM-LT, Fort Monmouth, NJ 07703.

The following companies manufacture aircraft batteries and may be contacted for technical assistance and pricing information:

Nickel-Cadmium Batteries

ACME Electric Corporation
Aerospace Division
528 W. 21st Street
Tempe, Arizona 85282
Phone (602) 894-6864

Eagle-Picher Industries, Inc.
3820 South Hancock Expressway
Colorado Springs, Colorado 80931
Phone (303) 392-4266

Marathon Power Technologies Company
8301 Imperial Drive
Waco, Texas 76712
Phone (817) 776-0650

SAFT America Inc.
711 Industrial Boulevard
Valdosta, Georgia 31601
Phone (912) 247-2331

Lead-Acid Batteries

Concorde Battery Corporation
2009 San Bernardino Road
West Covina, California 91790
Phone (818) 813-1234

Hawker Energy Products Ltd
Stephenson Street
Newport, Gwent NP9OXJ
United Kingdom
Phone (011) 441-633-277673

Teledyne Battery Products
840 West Brockton Avenue
Redlands, California 92374
Phone (909) 793-3131

Gregg F. Bartley "Boeing B-777: Fly-By- Wire Flight Controls"
The Avionics Handbook
Ed. Cary R. Spitzer
Boca Raton, CRC Press LLC. 2001