# BATTERY DESIGN

Proper design of the battery or the battery compartment is important to assure optimum, reliable, and safe operation. Many problems attributed to the battery may have been prevented had proper precautions been taken with both the design of the battery itself and how it is designed into the battery-operated equipment.
It is important to note that the performance of a cell in a battery can be significantly different from that of an individual cell depending on the particular environment of that cell in the battery. Specifications and data sheets provided by the manufacturers should only be used as a guide as it is not always possible to extrapolate the data to determine the performance of multicell batteries. Such factors as the cell uniformity, number of cells, series or parallel connections, battery case material and design, conditions of discharge and charge, temperature, to name a few, influence the performance of the battery. The problem is usually exacerbated under the more stringent conditions of use, such as high-rate charging and discharging, operation, and extreme temperatures and other conditions which tend to increase the variability of the cells within the battery.
Further, specific energy and energy density data based on cell or single-cell battery performance have to be derated when the weight and volume of the battery case, battery assembly materials, and any ancillary equipment in the battery have to be considered in the calculation.
Another factor that must be considered, particularly with newly developing battery technologies, is the difficulty of scaling up laboratory data based on smaller individual batteries
to multicell batteries using larger cells manufactured on a production line.

## DESIGNING TO ELIMINATE POTENTIAL SAFETY PROBLEMS
Batteries are sources of energy and when used properly will deliver their energy in a safe manner. There are instances, however, when a battery may vent, rupture, or even explode if it is abused. The design of the battery should include protective devices and other features which can prevent, or at least minimize, the problem. Some of the most common causes for battery failure are:
**1.** Short-circuiting of battery terminals
**2.** Excessive high rate discharge or charge
**3.** Voltage reversal, that is, discharging the cells of the battery below 0 V
**4.** Charging of primary batteries
**5.** Improper charge control when charging secondary batteries
These conditions may cause an internal pressure increase within the cells, resulting in an activation of the vent device or a rupture or explosion of the battery. There are a number of means to minimize the possibilities of these occurrences.

## Charging Primary Batteries
All major manufacturers of primary batteries warn that the batteries may leak or explode if they are charged. Some primary batteries can be recharged if done under controlled conditions.

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Nevertheless, charging primary batteries is not usually recommended because of the potential hazards.

**Protection from External Charge**
The simplest means of preventing a battery from being charged from an external power source is to incorporate a blocking diode in the battery pack, as shown in Figure 1. The diode chosen must have a current rating in excess of the operating current of the device. It should be rated, at a minimum, at twice the operating current. The forward voltage drop of the diode should be as low as possible. Schottky diodes are commonly used because of their typical 0.5V drop in the forward direction. Another consideration in selecting the diode is the reverse voltage rating. The peak inverse voltage (PIV) rating should be at least twice the voltage of the battery.
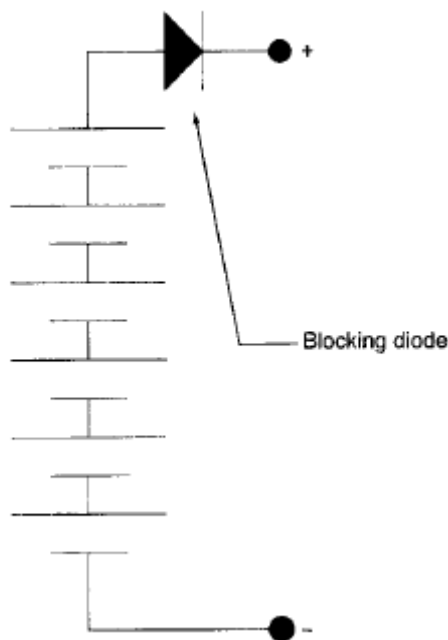
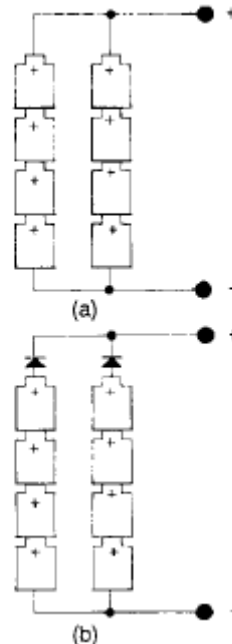Figure 1: Battery circuit incorporating a blocking diode to prevent charge.

Figure 2: Series / parallel battery
(*a*) Without diode protection
(*b*) With diode protection.

**Protection from Charging within Battery**
 When multiple series stacks are paralleled within a battery pack, charging may occur when a detective or a low-capacity cell is present in one of the stacks (Figure 2-a). The remaining stacks of cells will charge the stack with the defective cell. At best this situation will discharge the good stack, but it could result in rupture of the cells in the weak stack. To avoid this, diodes should be placed in each series string to block charging currents from stack to stack (Figure 2-*b*). When diode protection is used in each series stack, the diode will prevent the stack containing the defective cell from being charged. The diode should have the following characteristics:
**1.** Forward voltage drop should be as low as possible, Schottky type preferable.
**2.** Peak inverse voltage should be rated at twice the voltage of the individual series stack.

**3.** Forward current rating of the diodes should be a minimum of

$$I_{min} = \frac{I_{op}}{N} \times 2 \qquad \text{where } I_{op} = \text{device operating current} \\ N = \text{number of parallel stacks}$$

## Preventing Battery Short-Circuit Conditions
When a battery is short-circuited through the external terminals, the chemical energy is converted into heat within the battery. In order to prevent short-circuiting, the positive and negative terminals of the battery should be physically isolated. Effective battery design will incorporate the following:
**1.** The battery terminals should be recessed within the external case (Figure 3-*a*).
**2.** If connectors are used, the battery should incorporate the female connection. The connector should also be polarized to only permit for correct insertion (Figure 3-*b*).
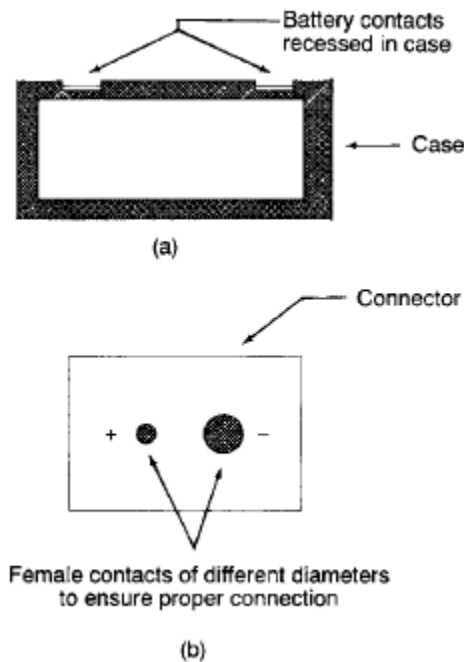


Figure 3: Design of battery terminals.

## Additional Short-Circuit Protection
In addition it may be also necessary to include some means of circuit interruption. There are a number of devices which can perform this function, including:
**1.** Fuses or circuit breakers
**2.** Thermostats designed to open the battery circuit when the temperature or current reaches a predetermined upper limit
**3.** Positive-temperature-coefficient (PTC) devices that, at normal currents and temperatures, have a very low value of resistance. When excessive currents pass through these devices or the battery temperature increases, the resistance increases orders of magnitude, limiting the current. These devices are incorporated internally in some cells by the cell manufacturer. When using cells with internal protection, it is advisable to use an external PTC selected to accommodate both the current and the voltage levels of the battery application.

## Voltage Reversal

Due to variability in manufacturing, capacities will vary from battery to battery. When discharged in a series configuration, the capacity of the weakest cell in the series string of a multicell battery will be depleted before the others. If the discharge is continued, the voltage of the low-capacity cell will reach 0 V and then reverse. The heat generated may eventually cause pressure buildup in the cell and subsequent venting or rupture. This process is sometimes referred to as ''forced discharge.'' A common test to determine the ability of cells to withstand voltage reversal is the forced discharge test. The cells are deliberately discharged, at specified currents, to below 0 V by other cells in a series string or by an external power supply to determine whether a venting, rupture, or other undesired safety problem arises. Some cells are designed to withstand a forced discharge to specified discharge currents.

The cells may also be designed with internal protection, such as fuses or thermal cutoff devices, to interrupt the discharge if an unsafe condition develops. This condition of cell unbalance could be exacerbated with rechargeable cells as the individual cell capacities could change during cycling. To minimize this effect, rechargeable batteries should at least be constructed with ''matched'' cells, that is, cells having nearly identical capacities. Cells are sorted, within grades, by at least one cycle of charge and discharge. Typically cells are considered matched when the capacity range is within 3%.

Recent advances in manufacturing control have reduced the number of cell grades. Some manufacturers have reached the optimal goal of one grade, which negates the need of matching. This information is readily available from the battery companies.

## Battery Design to Prevent Voltage Reversal

Even though matched cells are used, other battery designs or applications can cause an imbalance in cell capacity. One example is the use of voltage taps on cells of a multicell battery in a series string. In this design, the cells are not discharged equally. Figure 4 illustrates a battery incorporating voltage taps that could result in voltage reversal.
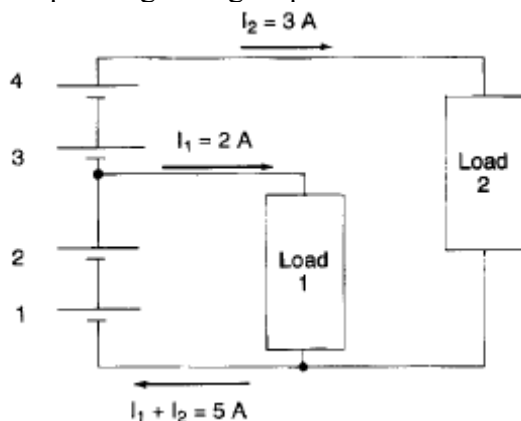


Figure 4: Battery circuit using voltage taps.

For illustration assume $I_2$ =3 A, $I_1$ =2 A, and the cell capacity is 15 Ah. Cells 3 and 4 are being discharged at the 5-h rate, while cells 1 and 2 are being discharged at the combination of $I_1 + I_2$, or 5 A, a 3-h rate. After 3 h, cells 1 and 2 will be almost depleted of capacity and will go into voltage reversal if the discharge is continued. Many early battery designs using Leclanche´-type cells incorporated the use of voltage taps. Batteries with as many as 30 cells in series (45 V)

were common with taps typically at 3, 9, 13.5 V, and so on. When the cells with the lower voltage taps were discharged, they could leak. This leakage could cause corrosion, but usually these cells would not be prone to rupture. With the advent of the high-energy, tightly sealed cells, this is no longer the case. Cells driven into voltage reversal may rupture or explode. In order to avoid problems, the battery should be designed with electrically independent sections for each voltage output. If possible, the device should be designed to be powered by a single input voltage source. DC to DC converters can be used to safely provide for multiple voltage outputs. Converters are now available with efficiencies greater than 90%.

### *Parallel Diodes to Prevent Voltage Reversal*

Some battery designers, particularly for multicell lithium primary batteries, add diodes in parallel to each cell to limit voltage reversal. As the cell voltage drops below zero volts and into reversal, the diode becomes conducting and diverts most of the current from flowing through the cell. This limits the extent of the voltage reversal to that of the characteristic of the diode. This use of diodes is shown in Figure 6 below.

### Protection of Cells and Batteries from External Charge

Many battery-powered devices are also operated from rectified alternating-current (AC) sources. These could include devices which offer both AC and battery operation or devices which use the battery for backup when the AC power supply fails or is not available. In the case where the battery is a backup for the main power supply as, for example, in memory backup, the primary battery must be protected from being charged by the main power supply. Typical circuits are shown in Figure 5. In Figure 5-*a* two blocking diodes are used redundantly to provide protection in case of the failure of one. A resistor is used in Figure 5-*b* to limit the charge current if the diode fails in a closed position. This blocking diode should have the features of a low voltage drop in the forward direction to minimize the loss of battery backup voltage, and a low leakage current in the reverse direction to minimize the charging current.
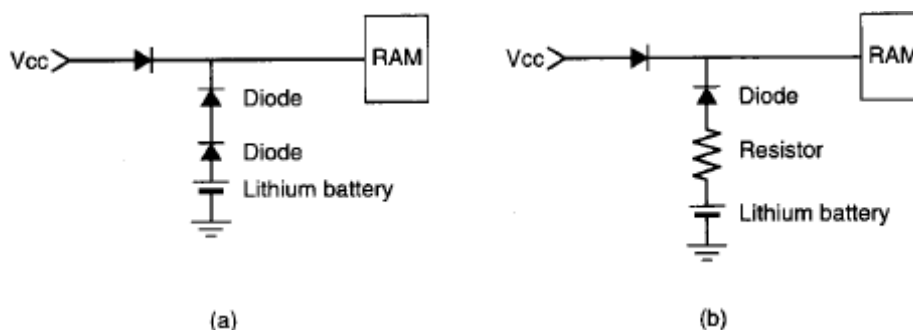


(a)                                                                             (b)

Figure 5: Protective circuitry for memory backup batteries. (*a*) Using two diodes. (*b*) Using diode and resistor, $V_{cc}$ = power supply voltage.

### Special Considerations When Designing Lithium Primary Batteries

Lithium primary batteries contain an anode of elemental lithium and, because of the activity of this metal, special precautions may be required in the design and use of the batteries, particularly when multiple cells are used in the battery pack. Some of the special precautions that should be taken in the design of these batteries, include the following:

**1.** When multiple cells are required, due to voltage and/or the capacity requirement of the

application, they should be welded into battery packs, thus preventing the user mixing cells of different chemistries or capacities if replaceable cells were used.

**2.** A thermal disconnect device should be included to prevent the build-up of excessive heat. Many of the batteries now manufactured include a PTC or a mechanical disconnect, or both, within the cell. Additional protective thermal devices should be included, external to the cells, in the design of a multicell battery pack.

**3.** The following protective devices should be included:

*a.* Series diode protection to prevent charging must be included

*b.* Cell bypass diode protection to prevent excessive voltage reversal of individual cells in a multicell series and/or series parallel configuration

*c.* Short circuit protection by means of a PTC, permanent fuse or electronic means, or a combination of all three

**4.** In order to make the used battery safe for disposal, for some lithium batteries the remaining lithium within the battery must be depleted. This is accomplished by placing a resistive load across the cell pack to completely discharge the battery after use. The resistive load should be chosen to ensure a low current discharge, typically at a five (5) day rate of the original capacity of the battery. This feature has been used mainly in military primary lithium batteries. Figure 6 illustrates a typical schematic showing the use of the safety features discussed.
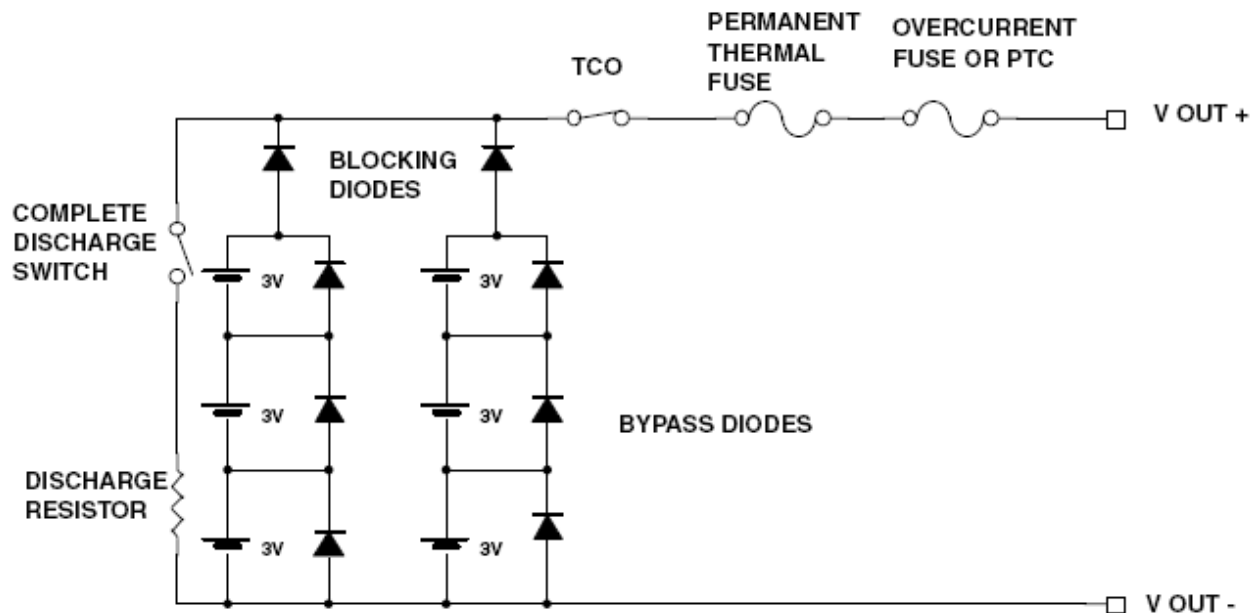


Figure 6: Lithium primary battery schematic with series and bypass protection.

## BATTERY SAFEGUARDS WHEN USING DISCRETE BATTERIES

**Design to Prevent Improper Insertion of Batteries**

When designing products using individual single-cell batteries, special care must be taken in the layout of the battery compartment. If provisions are not made to ensure the proper placement of the batteries, a situation may result in which some of the batteries that are improperly inserted could be exposed to being charged. This could lead to leakage, venting, rupture, or even explosion. Figure 7 illustrates simple battery-holder concepts for cylindrical and button batteries,

which will prevent the batteries from being inserted incorrectly. Figure 8 shows several other design options for preventing improper installation. Two commonly used battery circuits that are potentially dangerous without proper battery orientation are:

**1.** Series / parallel with one battery reversed (Figure 9). In this circuit, battery 3 has been reversed. As a result, batteries 1–3 are now in series and are charging battery 4. This condition can be avoided, if possible, by using a single series string of larger batteries. Further, as discussed above, the use of diodes in each series section will at least prevent one parallel stack from charging the other.

**2.** Multicell series stack with one battery reversed in position (Figure 10). The fourth battery is reversed and will be charged when the circuit is closed to operate the device. Depending on the magnitude of the current, the battery may vent or rupture. The magnitude of the current is dependent on the device load, the battery voltage, the condition of the reversed battery, and other conditions of the discharge.

To minimize the possibility of physically reversing a battery, the proper battery orientation should be clearly marked on the device, with simple and clear instructions. Blind battery compartments, where the individual batteries are not visible, should be avoided. The best practice is to use oriented or polarized battery holders, as discussed previously.
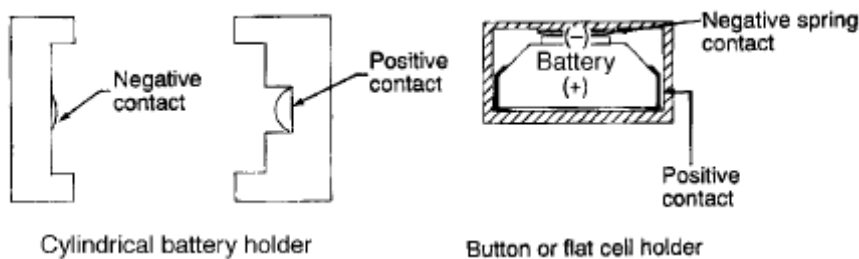


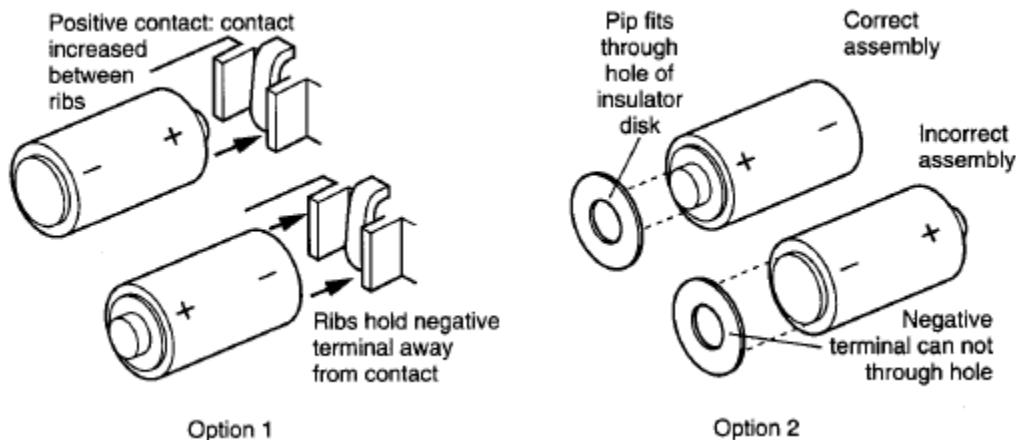Figure 7: Battery holders. (Left) Cylindrical. (Right) Button or flat.



Figure 8: Battery contact designs that prevent reverse installation of cells.
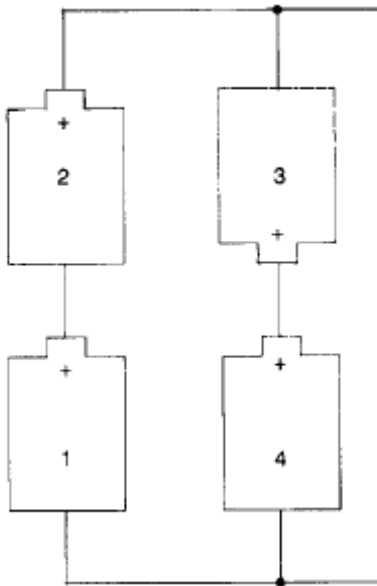
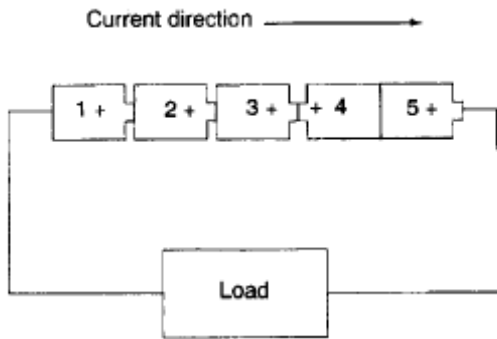Figure 9: Series / parallel circuit; cell 4 being charged.



Figure 10: One cell reversed in a series stack; cell 4 being charged.

**Battery Dimensions**

At times equipment manufacturers may design the battery cavity of their device around the battery of a single manufacturer. Unfortunately the batteries made by the various manufacturers are not exactly the same size. While the differences may not be great, this could result in a cavity design that will not accept batteries of all manufacturers. Along with variations in size, the battery cavity design must also be able to accommodate unusual battery configurations that fall within IEC standards. For example, several battery manufacturers offer batteries with negative recessed terminals that are designed to prevent contact when they are installed backward. Unfortunately negative recessed terminals will mate only with contacts whose width is less than the diameter of the battery's terminal. Figure 11-*a* illustrates the dimensional differences between cells with standard and recessed terminals.

The battery cavity should not be designed around the battery of a single manufacturer whose battery may be a unique size or configuration. Instead, cavity designs should be based on International Electrotechnical Commission (IEC) standards and built to accommodate maximum and minimum sizes. IEC and ANSI standards provide key battery dimensions, including overall height, overall diameter, pip diameter, pip height, and diameter of negative cap. Maximum and

minimum values are usually specified, as shown in Figure 11-*b*. As these standards are revised periodically, the latest edition should be used.
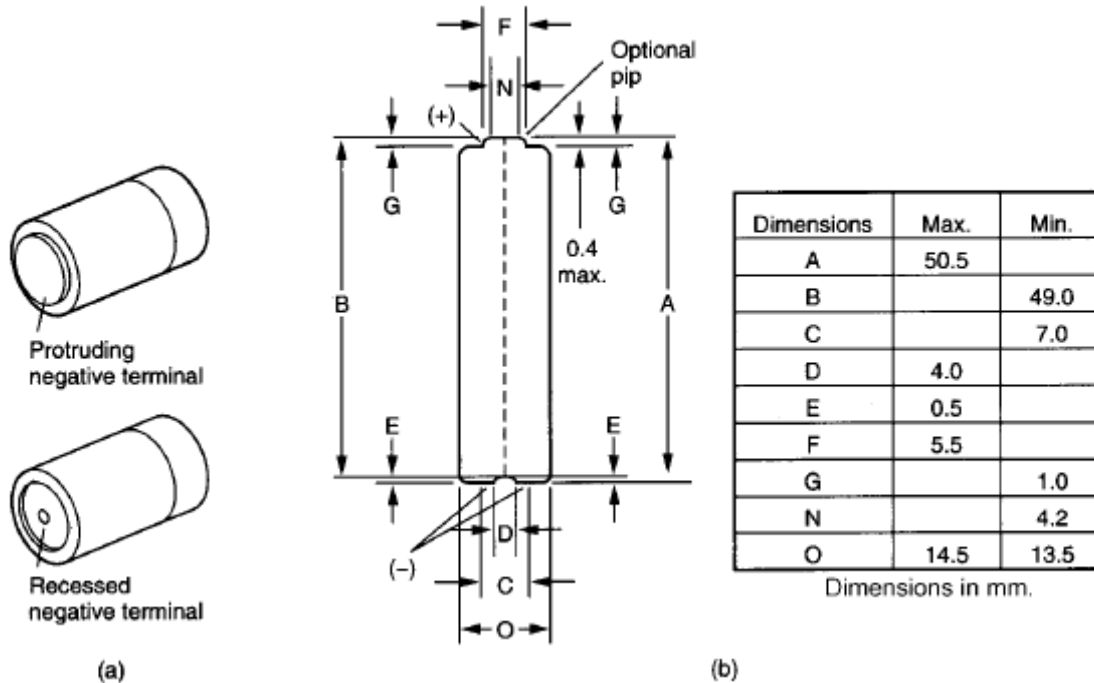


| Dimensions | Max. | Min. |
|---|---|---|
| A | 50.5 | |
| B | | 49.0 |
| C | | 7.0 |
| D | 4.0 | |
| E | 0.5 | |
| F | 5.5 | |
| G | | 1.0 |
| N | | 4.2 |
| O | 14.5 | 13.5 |

Dimensions in mm.

Figure 11: (*a*) Types of battery terminals falling within IEC standards. (*b*) Illustration of typical standard IEC dimensions.

## BATTERY CONSTRUCTION
The following constructional features also should be considered in the design and fabrication of batteries:
**1.** Intercell connections
**2.** Encapsulation of cells
**3.** Case configuration and materials
**4.** Terminals and contact materials

### Intercell Connections
Soldering is the method of connection for batteries using Leclanche´-type cells. Wires are soldered between the negative zinc can and the adjoining positive cap. This effective method of construction for these cells is still widely used.
Welding of conductive tabs between cells is the preferred method of intercell connection for most of the other battery systems. The tab materials for most applications are either pure nickel or nickel-plated steel. The corrosion resistance of the nickel and its ease of welding result in reliable permanent connections. The resistance of the tab material must be matched to the application to minimize voltage loss. The resistance can be calculated from the resistivity of the material, which is normally expressed in ohm-centimeters,

$$\text{Resistance} = \frac{\text{resistivity} \times \text{length (cm)}}{\text{cross-sectional area (cm}^2)}$$

The resistivity values of nickel and nickel-plated steel are

Nickel                     $6.84 \times 10^{-6} \ \Omega \cdot \text{cm}$

Nickel-plated steel        $10 \times 10^{-6} \ \Omega \cdot \text{cm}$

For example, the resistance of a tab with dimensions of 0.635 cm width, 0.0127 cm thickness, and 2.54 cm length is for nickel,

$$\frac{6.84 \times 10^{-6} \times 2.54}{0.635 \times 0.0127} = 2.15 \times 10^{-3} \ \Omega$$

And for nickel-plated steel,

$$\frac{10 \times 10^{-6} \times 2.54}{0.635 \times 0.0127} = 3.15 \times 10^{-3} \ \Omega$$

As is evident, the resistance of the nickel-plated steel material is 50% higher than that of nickel for an equivalent-size tab. Normally this difference is of no significance in the circuit, and nickel-plated steel is chosen due to its lower cost.

Resistance spot welding is the welding method of choice. Care must be taken to ensure a proper weld without burning through the cell container. Excessive welding temperatures could also result in damage to the internal cell components and venting may occur. Typically AC or capacitance discharge welders are used. Both types of welders incorporate two electrodes, typically made of a copper alloy. A current path is established between the electrodes, melting and fusion of the materials will occur at the interface of the tab and the cell due to resistance heating. Figure 12 illustrates the commonly used welding techniques. The method shown in Figure 12-*a* is used in more than 90% of the joints where a tab is welded to a cell surface. Two weld nuggets are formed for each weld action. When welding circular leads to a cell or tab surface, the procedure shown in Figure 12-*b* will result in one weld spot per weld action. The procedure in Figure 12-*c* is commonly used when a tab-to-tab weld or similar joints are needed. This latter method is not recommended for welding to a cell.
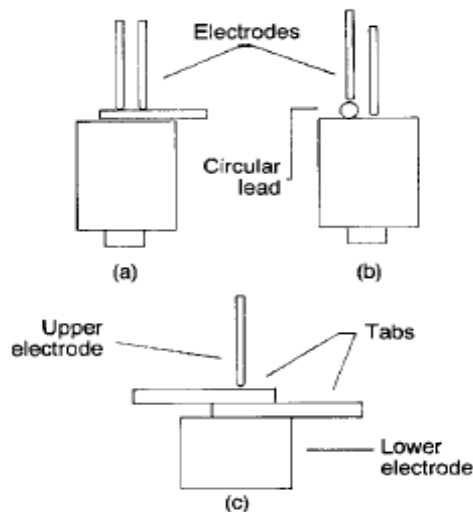


Figure 12: Various welding configurations used in battery construction.

In all instances the weld should have a clean appearance, with discoloration of the base materials kept to a minimum. At least two weld spots should be made at each connection joint. When the weld is tested by pulling the two pieces apart, the weld must hold while the base metal tears. For tabs the weld diameter, as a rule of thumb, should be three to four times the tab thickness. For example, a 0.125-mm-thick tab should have a tear diameter of 0.375–0.5 mm. Statistical techniques of weld pull strength for process control are helpful, but a visual inspection of the weld diameter must accompany the inspection process. The least preferred method of battery connection is the use of pressure contacts. Although this technique is used with some inexpensive consumer batteries, it can be the cause of battery failure where high reliability is desired. This type of connection is prone to corrosion at the contact points. In addition, under shock and vibration intermittent loss of contact may result.

**Cell Encapsulation**
Most applications require that the cells within the battery be rigidly fixed in position. In many instances this involves the encapsulation of the cells with epoxy, foams, tar, or other suitable potting materials. Care must be taken to prevent the potting material from blocking the vent mechanisms of the cells. A common technique is to orient the cell vents in the same direction and encapsulate the battery to a level below the vent, as shown in Figure 13. If possible the preferred method to keep the cells immobile, within the battery, is through careful case design without the use of potting materials. Although this method may increase initial tooling costs, future labor savings could be realized.
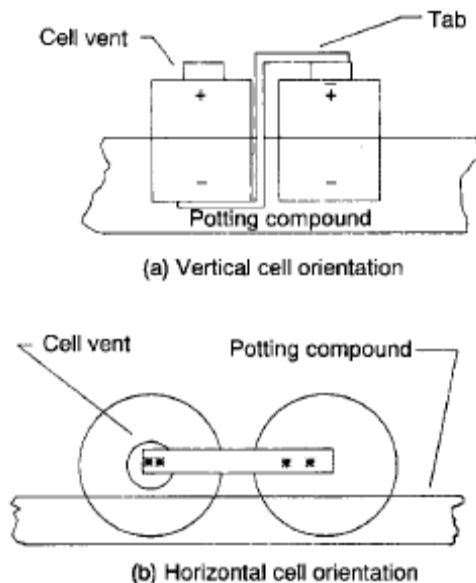


Figure 13: Battery encapsulation techniques. (*a*) Vertical cell orientation. (*b*) Horizontal cell orientation.

**Case Design**

Careful design of the case should include the following:

**1.** Materials must be compatible with the cell chemistry chosen. For example, aluminum reacts with alkaline electrolytes and must be protected where cell venting may occur.

**2.** Flame-retardant materials may be required to comply with end-use requirements. Underwriters Laboratories, the Canadian Standards Association, and other agencies may require testing to ensure safety compliance.

**3.** Adequate battery venting must allow for the release of vented cell gases. In sealed batteries this requires the use of a pressure relief valve or breather mechanisms.

**4.** The design must provide for effective dissipation of heat to limit the temperature rise during use and especially during charge. High temperatures should be avoided as they reduce charge efficiency, increase self-discharge, could cause cell venting, and generally are detrimental to battery life. The temperature increase is greater for a battery pack than for an individual or separated cells as the pack tends to limit the dissipation of heat. The problem is exacerbated when the pack is enclosed in a plastic case. This is illustrated in Figure 14, which compares the temperature rise of groups of cells with and without a battery case.
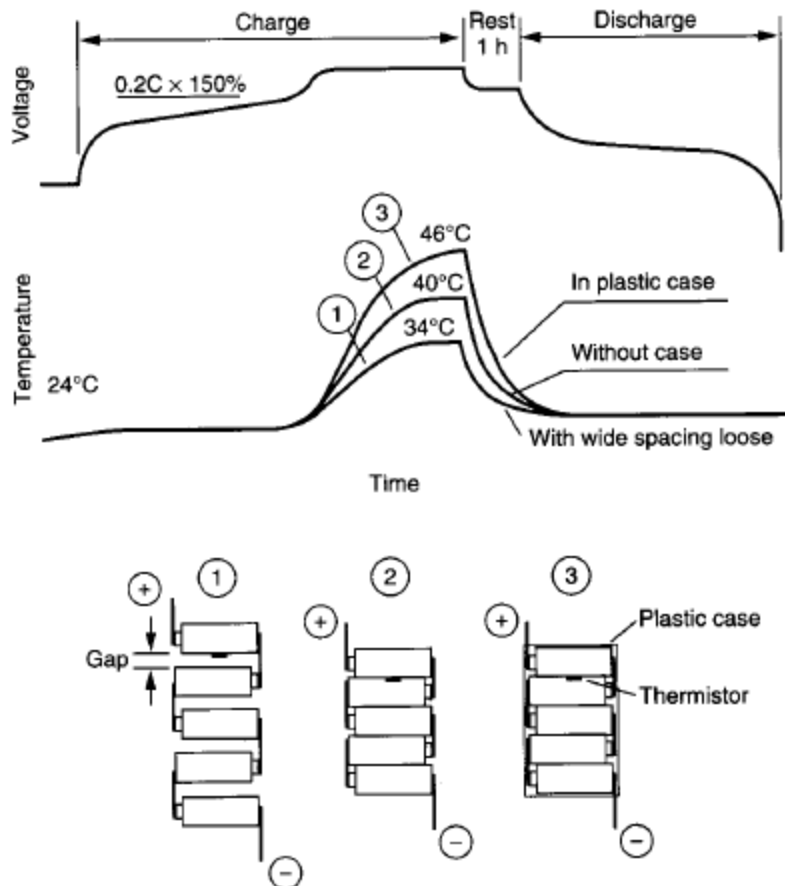


Figure 14: Temperature increase characteristics during charge of battery pack.

**Terminal and Contact Materials**

Terminal material selection must be compatible with the environments of the battery contents as well as the surroundings. Noncorrosive materials should be selected. Nickel-cadmium and Nickel–metal hydride batteries typically use solid nickel contacts to minimize corrosion at the terminal contacts. A number of factors must be considered when specifying contact materials. Several principles apply to the substrate. The normal force provided by the contact must be great enough to hold the battery in place (even when the device is dropped) and to prevent electrical degradation and any resulting instability. Contacts must be able to resist permanent set. This refers to the ability of the contact to resist permanent deformation with a set number of battery insertions. Temperature rise at high current drains due to the resistance of the contact material must be limited. Excessive temperature increase could lead to stress relaxation and loss in contact pressure as well as to the growth of oxide films which raise contact resistance.

A common way to minimize contact resistance is to provide a wiping action of the device contact to the battery contact when the battery is inserted in place. Most camcorder batteries incorporate this feature. Coatings should be selected to satisfy requirements not met by the substrate material, such as conductivity, wear, and corrosion resistance. Gold is an optimal coating due to its ability to meet most of the requirements. However, other materials may be used. Table 1 lists the characteristics of various materials used as contacts.

Table 1: Contact Materials

| | |
|---|---|
| Gold plating | Provides the most reliable metal-to-metal contact under all environmental conditions |
| Nickel (solid) | Provides excellent resistance to environmental corrosion and is second only to gold plating as a contact material; material can be drawn or formed. |
| Nickel-clad stainless steel | Performs almost as well as solid nickel, with excellent resistance to environmental corrosion |
| Nickel-plated | Very good material; unplated stainless steel is not recommended due to the adverse impact of passive films which develop on stainless steel resulting in poor electrical contact |
| Inconel alloy | Provides good electrical conductivity and good corrosion resistance; if manufacturers prefer to solder the contact piece in the circuit, soldering may be difficult unless an active flux is used |
| Nickel-plated cold-rolled steel | The most economical contact material; continuous, nonporous nickel plating of 200 μm is preferred. |

**DESIGN OF RECHARGEABLE BATTERIES**

All of the criteria addressed for the design of primary batteries should be considered for the design of rechargeable batteries. In addition, multicell rechargeable batteries should be built using cells having matched capacities. In a series-connected multicell battery, the cell with the lowest capacity will determine the duration of the discharge, while the one with the highest capacity will control the capacity returned during the charge. If the cells are not balanced, the battery will not be charged to its designed capacity. To minimize the mismatch, the cells within a

multicell battery should be selected from one production lot, and the cells selected for a given battery should have as close to identical capacities as possible. This is especially important with lithium-ion batteries, because due to the need for limiting current during charge, it is not possible to balance the capacity of the individual cells with a top-off or trickle charge. Furthermore, safeguards must be included to control charging to prevent damage to the battery due to abusive charging. Proper control of the charge process is critical to the ultimate life and safety of the battery. The two (2) major considerations to be addressed include:

**1.** Voltage and current control to prevent overcharge

**2.** Temperature sensing and response to maintain the battery temperature within the range specified by the battery manufacturers.

**Charge Control**

The controls for voltage and current during charge for most batteries are contained in the charger. Nickel–cadmium and nickel–metal hydride batteries may be charged over a fairly broad range of input current, ranging from less than a 0.05C rate to greater than 1.0C. As the charge rate increases, the degree of charger control increases. While a simple, constant current control circuit may be adequate for a battery being charged at a 0.05C rate, it would not suffice at a rate of 0.5C or greater. Protective devices are installed within the battery to stop the charge in the event of an unacceptable temperature rise. The thermal devices that can be used include the following:

**1.** *Thermistor:* This device is a calibrated resistor whose value varies inversely with temperature. The nominal resistance is its value at $25^{o}$C. The nominal value is in the Kohm range with 10K being the most common. By proper placement within the battery pack, a measurement of the temperature of the battery is available and $T_{max}$, $T_{min}$ and $\Delta T/\Delta t$ or other such parameters can be established for charge control. In addition, the battery temperature can be sensed during discharge to control the discharge, e.g., turn off loads to lower the battery temperature, in the event that excessively high temperatures are reached during the discharge.

**2.** *Thermostat* (*Temperature Cutoff, TCO*): This device operates at a fixed temperature and is used to cut off the charge (or discharge) when a preestablished internal battery temperature is reached. TCOs are usually resettable. They are connected in series within the cell stack.

**3.** *Thermal Fuse:* This device is wired in series with the cell stack and will open the circuit when a predetermined temperature is reached. Thermal fuses are included as a protection against thermal runaway and are normally set to open at approximately $30$–$50^{o}$C above the maximum battery operating temperature. They do not reset.

**4.** *Positive Temperature Coefficient* (*PTC*) *Device:* This is a resettable device, connected in series with the cells, whose resistance increases rapidly when a preestablished temperature is reached, thereby reducing the current in the battery to a low and acceptable current level. The characteristics of the PTC device are shown in Figure 15. It will respond to high circuit current beyond design limits (such as a short circuit) and acts like a resettable fuse. It will also respond to high temperatures surrounding the PTC device, in which case it operates like a temperature cutoff (TCO) device.

Figure 16 shows a schematic of a battery circuit, indicating the electrical location of these protective devices. The location of the thermal devices in the battery assembly is critical to ensure that they will respond properly as the temperature may not be uniform throughout the

battery pack. Examples of recommended locations in a battery pack are shown in Figure 17. Other arrangements are possible, depending on the particular battery design and application. Details of the specific procedures for charging and charge control are covered in the various chapters on rechargeable batteries.
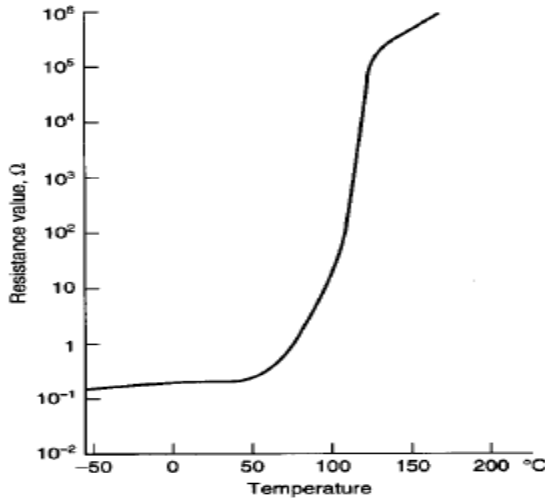


Figure 15: Characteristics of a typical positive temperature coefficient (PTC) device.
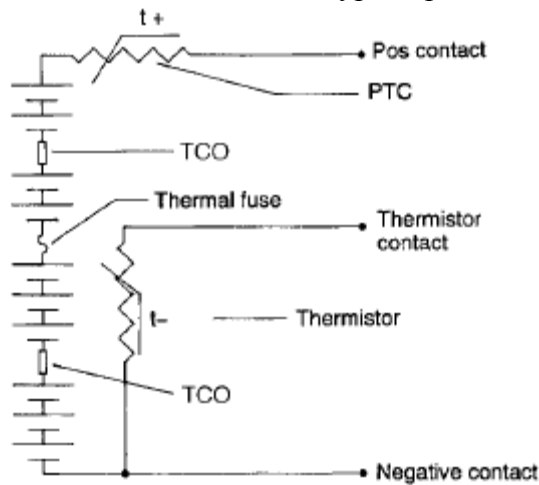


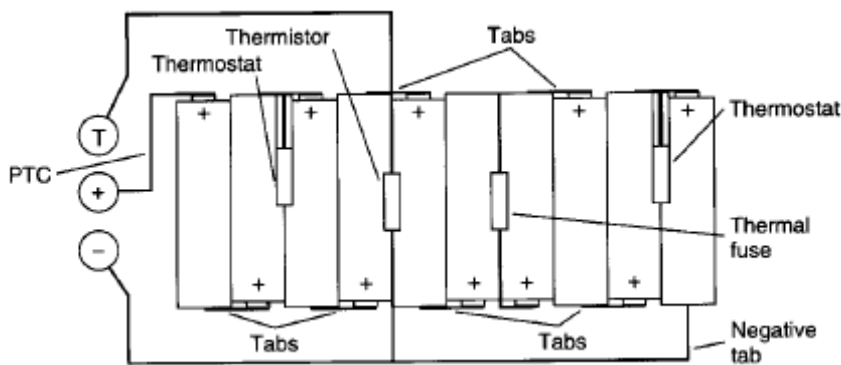Figure 16: Protective devices for charge control.



Figure 17: Location of protective devices in battery.

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**Example of Discharge/Charge Control**

Electronic circuitry can be used to maximize battery service life by cutting off the discharge as close to the specified end or cut-off voltage as possible. Ending the discharge at too high a voltage will result in a loss of a significant amount of battery capacity; ending it at too low an end voltage and, thus, discharging the battery beyond its safe cut-off could cause permanent damage to the battery. Similarly, on charge, accurate control, as discussed above, will enable a maximum charge under safe conditions without damage to the battery. This is especially important for the lithium-ion battery for which the preferred charge protocol for a high rate charge is to start the charge at a relatively high, usually constant current to a given voltage and then taper charging at a constant voltage to a given current cutoff. Exceeding the maximum voltage is a potential safety hazard and could cause irreversible damage to the battery. Charging to a lower voltage will reduce the capacity of the battery. Another interesting example is the control of charge for hybrid electric vehicles (HEV). In this application, it is advantageous to obtain close to 100% charge efficiency or charge acceptance rather than maximum battery capacity. The charge acceptance for a battery at the low state-of-charge (SOC) is close to 100%. As the battery is charged, charge acceptance becomes progressively poorer, particularly above 80% SOC. (At full charge, the charge acceptance is zero). In the HEV application using nickel-metal hydride batteries, the charge control keeps the stage-of-charge, under normal driving and regenerative braking conditions, as close to 50% SOC as possible, and preferably within 30 to 70%. At these states-of-charge, the coulombic charge efficiency is very high. Other useful information also can be included in the chip, such as manufacturing information, chemistry, design data serial number, and cycle count.

**Lithium-Ion Batteries**

Special controls should be used with Lithium-ion batteries for management of charge and discharge. Typically, the control circuit will address the following items that affect battery life and safety.

*Cell Voltage:* The voltage of each individual cell in the battery pack is monitored on a continuous basis. Depending on the specific lithium-ion battery chemistry that is used, the upper voltage limit on charge, as specified by the manufacturer, is usually limited between 4.1 to 4.3 volts. On discharge, the cell voltage should not fall below 2.5 to 2.7 volts.

*Temperature Control:* As with any battery system, high temperature will cause irreversible damage. Internal battery temperature, for most applications, should be kept below $75^{o}$C. Temperature cutoff, with a trip of $70^{o}$C and reset temperature in the range of $45^{o}$C, is routinely used. Temperatures in excess of $100^{o}$C could result in permanent cell damage. For this, permanent type fuses are used; typically set for $104^{o}$C with a tolerance of +/- $5^{o}$C.

*Short Circuit Protection:* Normally, current limits are incorporated into the protection circuits. As a backup, a PTC device or fuse is placed in series with the battery pack. It is advisable to place the PTC between the pack assembly and the output of the battery. By placing it at this point, the PTC will not interfere with the operation of the upper or lower voltage detection of the electronic control circuit.

*ELECTRONIC ENERGY MANAGEMENT AND DISPLAY—"SMART" BATTERIES*
During the past decade, an important development in rechargeable battery technology has been the introduction of the use of electronic microprocessors to optimize the performance of the battery, control charge and discharge, enhance safety and provide the user with information on the condition of the battery. The microprocessor can be incorporated into the battery (the so-called *smart battery*), into the battery charger, or into the host battery-using equipment.
Some of the features include:
**1.** *Charge control.* The microprocessor can monitor the battery during charge controlling charge rate and charge termination, such as *t*, $V_{max}$, $-\Delta V$, $\Delta T$, and $\Delta T/\Delta t$, to cut off the charge or to switch to a lower charge rate or another charge method. Constant current to constant voltage charge can be controlled and options can be incorporated into the chip for pulse charging, "reflex" charging (a brief periodic discharge pulse during charge), or other appropriate control features.
**2.** *Discharge control.* Discharge control is also provided to control such conditions as discharge rate, end-of-life cutoff voltage (to prevent overdischarge), cell equalization and temperature management. Individual cells, as well as the entire battery pack, can be monitored to maintain cell balance during cycling.
**3.** *State-of-charge indicator.* These devices, commonly known as "gas gauges," estimate the remaining battery capacity by factoring in such variables as the discharge rate and time, temperature, self-discharge, charge rate and duration. The remaining capacity is normally displayed by a sequence of illuminated LEDs or as a direct output to the device being powered.
**4.** *Other information.* Data is collected during the life of the battery to update the database and, as needed, make changes to maintain optimum performance. Other information can also be included or collected, such as battery chemistry and characteristics, manufacturing information (battery manufacturer can electronically "stamp" batteries at time of manufacture) and battery history, cycle count and other such data for a complete accounting of the battery's usage.
There are several main elements to consider in the design of smart batteries:
**1.** *Measurement.* There are several parameters that can be measured directly to provide the basic information for the microprocessor. These include voltage, current, temperature and time. It is important that these measurements be made as accurately as possible to provide the best data for control. For example, voltage measurements are critical as the charge control (charge termination) depends on the battery voltage which, in some instances, should be accurate to at least 0.05 volts. An inaccurate measurement could result in under or overcharge which could result in short service life or damage to the battery, respectively. Or, in the case of the lithium-ion battery, overcharge could be a safety hazard. Similarly, on discharge, cutting off the discharge prematurely results in an unnecessarily shortened service life while overdischarge could, again, result in damage to the battery. Errors in the measurement of current affect not only the calculation of capacity and the state-of-charge "gas gauge," but influence the termination of charge and discharge as the termination voltages may vary depending on the current. Complicating this measurement is that the current is not a constant value, particularly during the discharge, with multiple power modes and high current pulses as short as milliseconds. Likewise, temperature is an important parameter as the performance of batteries is highly temperature dependent and exposure to high temperatures can cause irreversible damage to the cells.

**2.** *Calculation.* The calculation step covers the procedures for using the measured data as well as the algorithms to estimate battery performance (e.g. capacity at various discharge loads and temperature), charge acceptance, self-discharge, etc. Early ''smart battery'' electronics used simple linear models for these parameters which severely limited the accuracy in predicting the battery's performance. As noted in the descriptions of battery performance in the various chapters in this Handbook, battery performance, e.g. with respect to current drain and temperature is not linear. Self-discharge, similarly, is a complex relationship influenced at least by temperature, time, state of charge and the discharge load at which it is measured. Further, the performance of even those batteries using the same chemistry, varies with design, size, manufacturer, age, etc. A good algorithm will account for these relationships for control, predicting remaining service life and assuring safe operation.

**3.** *Communication.* Clear, accurate and secure communication is important between the battery and host charger and the battery-using equipment for each component to obtain data or provide needed data to one of the other components. For example, the battery charger must be informed of the characteristics of the battery it is charging, the battery's state of charge, charge voltage and current requirements, charge-off, etc. The smart battery must also communicate to the user who may require information, such as remaining battery life, power levels, charge time and other characteristics to facilitate the use of the equipment.

**4.** *Errors.* As discussed under *Measurement,* it is important that parameters be measured accurately as inaccurate ones would not only result in incorrect decisions on the battery's capability but could result in damage to the battery or safety problems. In addition, the Smart Battery provides information on the margin-of-error in the state-of-charge calculation. This function is called ''MaxError'' and has a range of 0 to 100%. If the ''MaxError'' displays 20% and the ''State-of-Charge'' displays 30%, the actual state-of charge is between 30 and 50%. If this loss of capacity is due to self-discharge while the battery is on stand and the rate of self-discharge does not follow the installed algorithm, the ''MaxError'' will increase. The user can correct this by, for example, fully charging the battery after a full discharge. This will restore the battery to full capacity and the battery will sense the ''Reset'' condition and return the MaxError to zero. It is possible to output an alarm when the MaxError has reached a programmed limit, alterting the user that a reset cycle is warranted.

**The Smart Battery System**
In order to ensure effective communication between the battery and host device, standard methods of communication are required. One method developed by battery manufacturers and microprocessor companies is the Smart Battery System (SBS) based on the System Management Bus. In 1995, the ''Smart Battery Data Specification'' was released by the SBS Forum. These specifications detail the communications method, protocols and the data interfaces between various devices. The goal of the Smart Battery interface is to provide adequate information for power management and charge control regardless of the particular battery's chemistry. Even though the major consumer of the battery information is the user, the system can also take advantage by using power consumption information to better manage its own power use. A charging system will be able to tell the user how long it will take to fully charge the battery. One possible Smart Battery model is a system consisting of a battery, battery charger and a host

(notebook computer, video camera, cellular phone, or other portable electronic equipment) as illustrated in Figure 18.
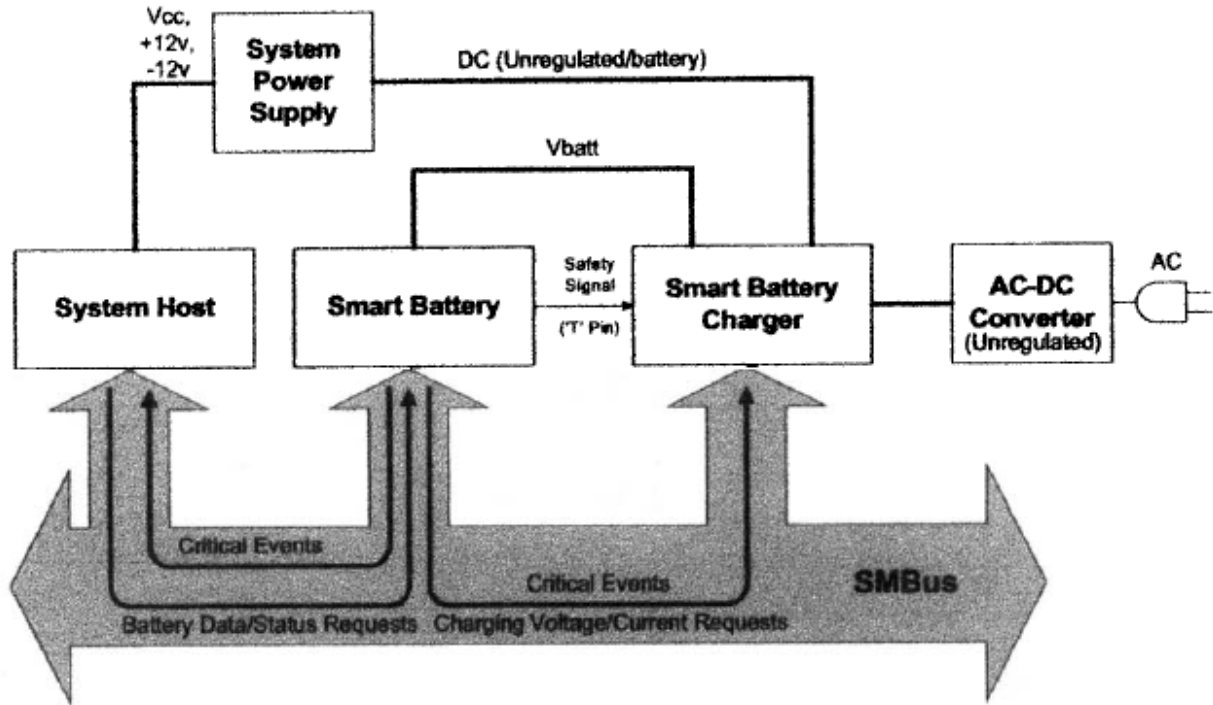


Figure 18: Outline of a Smart Battery System .

The Smart Battery consists of a collection of cells or single-cell batteries and is equipped with specialized hardware that provides present state, calculated and predicted information to its SMBus Host. These may monitor particular environmental parameters in order to calculate the required data values. The electronics need not be inside the Smart Battery if the battery is not removable from the device.

The Smart Battery communicates with the other devices (such as the SM (System Management) Bus Host and the Smart Battery Charger) via two separate communication interfaces:

The first uses the SMBus CLOCK and DATA lines and is the primary communication channel between the Smart Battery and other SMBus devices. The Smart Battery will provide data when requested, send charging information to the Stuart Battery Charger, and broadcast critical alarm information when parameters (measured or calculated) exceed predetermined limits within the particular Smart Battery. The other required communication interface is the secondary signaling mechanism or 'Safety Signal' on a Smart Battery pack connector. This is a variable resistance output from the Smart Battery which indicates when charging is permitted. It is meant as an alternate signaling method should the SMBus become inoperable. It is primarily used by the Smart Battery Charger to confirm correct charging.

The Smart Battery Charger is a charging circuit that provides the Smart Battery with charging current and charging voltage to match the Smart Battery's requested requirements. The battery charger periodically communicates with the Smart Battery and alters its charging characteristics in response to information provided by the Smart Battery. This allows the battery to control its

own charge cycle. Optionally, the Smart Battery Charger may not allow the Smart Battery to supply power to the rest of the system when the Smart Battery is fully charged and the system is connected to AC power, thus prolonging the life of the battery.

The Smart Battery Charger will also receive critical events from the Smart Battery when it detects a problem. These include alarms for charging conditions or temperature conditions which exceed the limits set within the particular Stuart Battery.

The SM Bus is a specific implementation of a PC-bus that describes data protocols, device addresses and additional electrical requirements that is designed to physically transport ommands and information between the components of the Smart Battery system.

The SMBus Host represents a piece of electronic equipment that is powered by a Smart Battery and that can communicate with the Smart Battery. The SMBus Host requests information from the battery and then uses it in the systems power management scheme and/or uses it to provide the user information about the battery's state and capabilities. The SMBus Host will also receive critical events from the Smart Battery when it detects a problem. In addition to the alarms sent to the Smart Battery Charger, it receives alarms for end of discharge, remaining capacity below the user set threshold value and remaining run time below the user set threshold value.

Figure 19 is a schematic block diagram of a Smart Battery system, in this case for a three cell Lithium-Ion battery.
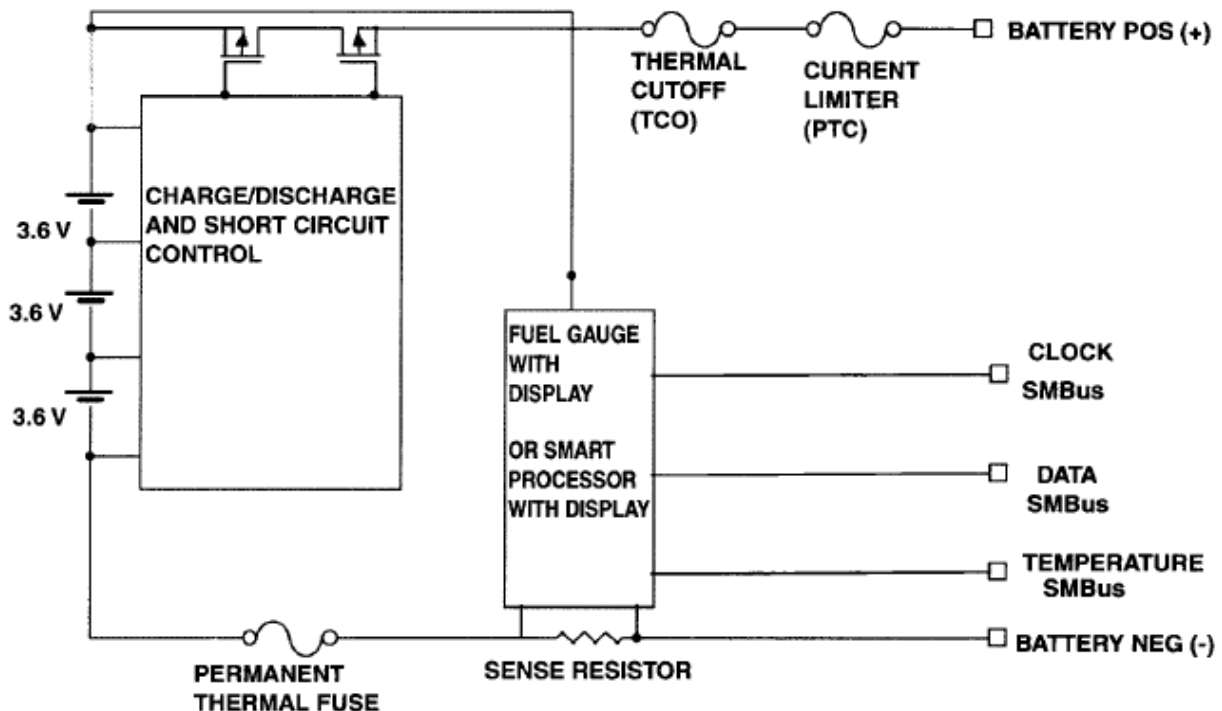


Figure 19: Schematic block diagram of a Lithium Ion three cell battery with SMBus output or gas gauge display.

The battery incorporates five terminals, battery plus and minus, clock, data and a safety signal, typically temperature. If the battery is hard wired into the host, the electronics need not be inside the battery. When the mechanical construction is complete, it must be programmed with the information such as chemistry, charge current, maximum voltage, etc. The information that is available to the host and charger includes:

**1.** Charge instructions for voltage, current and temperature
**2.** Battery design capacity
**3.** Remaining time to full charge
**4.** Remaining run time
**5.** Operating voltage, current, power, and temperature
**6.** Battery cycle count
**7.** Manufacturer's name, model, serial number and date of manufacture
**8.** Other information.

## GUIDELINES
In addition to the material aforementioned, the following should be considered in the design and fabrication of batteries:

**1.** Allow for the thermal expansion of battery components as well as the change in cell volume which accompanies discharge.
**2.** Consider the implications of cell leakage on equipment components, intercell weld or solder connections, and other battery components such as potting compounds, wire insulation, and adhesives. Locate the battery compartment in the device, such as to minimize the effects of possible leakage.
**3.** Wire leads and intercell connectors should be properly isolated and insulated to preclude the development of short circuits during the assembly process as well as during the life of the battery.
**4.** Intercell and battery connections need to be carefully made to withstand the severity of the equipment environment. Intercell connections shall be welded rather than soldered to avoid heat conduction to the interior of the cell.
**5.** Handle cells carefully to avoid inadvertent short circuits and discharge.
**6.** Avoid the use of high-exotherm potting compounds during battery fabrication.
**7.** Always vent the battery compartment in the device, allowing for release of any buildup of gas pressure. Avoid any confined pockets in the device where these gases may accumulate.