Safety Guard

Overvoltage protection for LiPo cell/pack charging

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Executive summary

Lithium Polymer (LiPo) chemistry is the next generation electric power technology for radio control applications. As with any new technology, modelers must learn how to safely handle, charge and use LiPo cells and packs.

With more than one million cells used in radio control applications, LiPo technology has an excellent safety record. Based on field reports, most safety concerns are associated with LiPo charging.

Safety Guard, an inexpensive accessory offered by FMA, provides a first line of defense against overvoltage during charging. Safety Guard is available in three models for use with 2-cell, 3-cell and 4-cell series-connected LiPo packs.

Safety Guard's primary application is to prevent overvoltage when charging LiPo packs with a current-regulated LiPo charger. Connected between charger and pack, Safety Guard limits charge voltage to 4.2 volts per cell. When Safety Guard's output voltage exceeds this amount, Safety Guard disconnects the pack from the charger—minimizing the chance of cell damage and dangerous conditions.

A second application* for Safety Guard is to charge LiPo packs from sources not specifically designed for that purpose, such as certain wall plug-in DC power supplies, radio control transmitter chargers, high current sources (e.g., lead acid batteries and DC power supplies), and 1-7 cell NiCd/NiMH fast chargers.

A third application* for Safety Guard is to prevent LiPo packs from being discharged below 2.5 volts per cell (a condition that lowers pack performance and life). Because Safety Guard disconnects the LiPo pack from the current drain in this application, uses in radio control are limited.

Used with recommended charging and handling procedures, Safety Guard helps modelers obtain maximum performance and life from their LiPo packs.

FMA is dedicated to helping radio control modelers (and other users) safely handle, charge and use LiPo technology. For additional LiPo documentation, see *www.fmadirect.com > Support > Application Notes*.

*** CAUTION:** The second and third applications require detailed knowledge of the charging source. Those specifications can be found in "Appendix: Safety Guard applications," later in this paper.

Introduction

Lithium Polymer (LiPo) chemistry is the next generation electric power technology for radio control applications. In the coming years, LiPo is expected to largely replace NiCd and NiMH for powering receivers, servos and electric motors. As with any new technology, modelers must learn how to safely handle, charge and use LiPo cells and packs.

In commercial and consumer applications, LiPo cells/packs are equipped with Protective Circuit Modules (PCMs). A PCM prevents two conditions known to damage LiPo cells: overvoltage during charging and undervoltage during discharging. It's important to avoid these conditions because:

- Overvoltage during charging rapidly destroys cells—and in the worst case, causes cells to vent with flames.

- Undervoltage during discharge dramatically shortens cell life.

PCMs, however, are not common in radio control applications. As a result, radio control modelers must adopt new approaches when using LiPo cells and packs. When powering a receiver/servo system, for example, a 2-cell LiPo pack requires a voltage regulator to drop its nominal 7.4 volt output to 5.0 volts. New electronic speed control (ESC) designs—with damage-preventing low voltage cutoff—are becoming available for powering electric aircraft motors from LiPo.

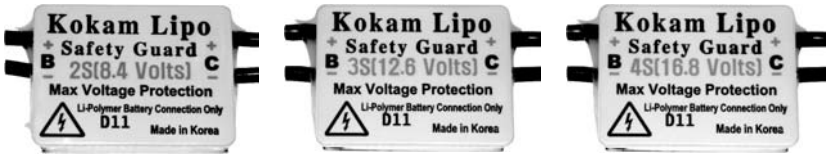
Based on field reports, most safety concerns are associated with LiPo charging. FMA's Safety Guard provides a first line of defense against overvoltage during charging.

Safety Guard

FMA's Safety Guard is an inexpensive protective circuit with three applications:

- Overvoltage protection for LiPo chargers.
- Charging with non-LiPo chargers (with limitations and precautions).
- Undervoltage protection in certain situations.

Safety Guard is available in three ratings for 2s, 3s and 4s packs:



Overvoltage protection with LiPo chargers

Safety Guard's primary application is to prevent overvoltage when charging LiPo packs with a current-regulated LiPo charger. Many LiPo chargers have selectable output voltages for charging LiPo packs in various configurations (2s, 3s, 4s, etc.). If you accidentally apply a too-high voltage to a pack, the pack will be damaged or destroyed. An example would be attempting to charge a 2s pack (7.4V) with voltage intended for a 3s pack (11.1V). A 2s Safety Guard between the charger and pack would prevent overvoltage damage in this example.

Connected between charger and pack, Safety Guard limits charge voltage to 4.2 volts per cell (see "What does 'volts per cell' mean?," later in this paper). When Safety Guard's output voltage exceeds this amount, Safety Guard disconnects the pack from the charger—minimizing the chance of cell damage and dangerous conditions.

Note: "Appendix: Safety Guard applications" provides details on charging setups discussed in this chapter.

Charging with non-LiPo chargers

A second application for Safety Guard is to charge LiPo packs from sources not specifically designed for that purpose. Such sources include:

- Certain wall plug-in DC power supplies.
- Radio control transmitter chargers.
- High current sources such as a 12V lead-acid battery or variable voltage DC power supply.
- NiCd/NiMH fast chargers for up to 7 NiCd cells.

Undervoltage protection

A third application for Safety Guard is to prevent LiPo packs from being discharged below 2.5 volts per cell. When discharged below 2.5 volts per cell, LiPo pack performance and life rapidly decrease. Because Safety Guard disconnects a LiPo pack from the current drain in this application, uses in radio control are limited.

Recommended LiPo charging system

Safety Guard is one of the items in a basic setup for charging LiPo packs, which includes:

- Current-limited LiPo charger, such as the FMA LIPO-403.
- Power source for charger (e.g., 11 to 15VDC battery or power supply for the LIPO-403).
- 2s, 3s or 4s Safety Guard (corresponding to LiPo pack configuration).
- 2s, 3s or 4s Kokam USA LiPo pack.
- Charging area: a non-combustible surface or enclosure away from flammable materials.
- An alert person to monitor charging.

LiPo safety

At this writing, there are more than one million LiPo cells being used in radio control applications. This usage represents many millions of charges and discharges. The safety record for Lithium cells in radio control is excellent, particularly considering that:

- Both manufacturers and modelers are learning how to use and handle the cells.
- Most modelers use the cells with no protective circuit during charge or discharge.
- Many chargers and charging methods are used.

There have been a few reports of cells damaged by overcharge. In a very few instances, there has been venting with flames. In almost all cases, the cause has been known or was deduced from analysis of the situation. Nearly all these problems were related to charging. (One non-charging incident involving a Lithium pack of unknown manufacture occurred because the modeler crashed an airplane and placed it in his car without removing the shorted pack.)

Potential causes of cell damage fall into three categories:

- **Charging**
  - Overvoltage during charge, including incorrect selection of charge voltage.[1]
  - Sudden peak surge voltage from the charger when disconnecting.
  - High current rapid charging by users who assumed LiPo can be charged at high current like some NiCd cells can.
  - Use of chargers not designed for LiPo chemistry.[2]
  - Unreliable chargers. In some chargers with FET switching, the FET shorts when it fails and full supply voltage is applied to the cell.[1] This can be avoided if appropriate crowbar protection[3] or foldback[4] is designed into the charger.

- **Discharging**
  - Excessive discharge rate.
  - Undervoltage during discharge.[1]

[1] Safety Guard can help prevent this cause of cell damage.
[2] Safety Guard is a partial aid for this situation.
[3] Crowbar is an overvoltage protection circuit which rapidly places a low resistance shunt across the power supply output terminals if a predetermined voltage is exceeded. The charger must be fused so that the fuse blows when the crowbar activates.
[4] A power supply output protection circuit whereby the output current decreases with increasing overload, reaching a minimum at short circuit. This minimizes internal power dissipation under overload conditions.

- **Construction, handling and other factors**
  - Faulty pack assembly.
  - Use of aluminum soldering paste that deteriorates the tabs and causes a short circuit.
  - Cell failure that creates an instant unbalance in the pack.
  - Fundamental risk of ignition when lithium is exposed to air entering through a damaged cell envelope.
  - Physical damage and abuse. (For example, accidentally running a T-pin through a fully charged cell will short all plates.)

All high energy density cells used for RC, including NiCd, NiMH, lead acid and LiPo, pose an electrical hazard. If wiring or interconnects are poor or become shorted, these cells are capable of delivering such high currents that the wiring can burn like a filament. Should the pack or wiring be in contact with flammable material, a fire will result.

Additional precautions are in order. If shorted, all high energy density cells (including LiPo cells) can heat rapidly, rupturing the envelope or case. A wiring harness connected to a cell or battery, if shorted, can glow like a filament and cause ignition of flammable materials.

All high energy density cells, including LiPo cells, are safe when handled, interconnected, charged and discharged according to manufacturers' recommendations, accepted industry practices and common sense. FMA provides a set of precautions for use of the cells and packs it sells. The precautions are listed below, and are also provided on the FMA Direct Web site.

WARNING

Safety precautions for Lithium Polymer and NiCd cells/packs stocked by FMA Direct

1. Never fast-charge any battery type unattended.
2. Never charge LiPo cells/packs at any rate unattended.
3. Only charge LiPo cells/packs with a charger designed specifically for lithium polymer chemistry. Example chargers include the Kokam USA, LIPO 402, LIPO 102 and LIPO 202; Bishop Power Products Apache S1215 and S1500; Great Planes Triton; and Schulze chargers with lithium charging capability.
4. LiPo cells can ignite because of unmatched cell capacity or voltage, cell damage, charger failure, incorrect charger settings and other factors.
5. Always use the correct charging voltage. LiPo cells/packs may ignite if connected to a charger supplying more than 6 volts per cell.
6. Always assure the charger is working properly.
7. Always charge LiPo cells/packs where no harm can result, no matter what happens.
8. Never charge a cell/pack in a model. A hot pack may ignite wood, foam or plastic.
9. Never charge a cell/pack inside a motor vehicle, or in a vehicle's engine compartment.
10. Never charge a cell/pack on a wooden workbench, or on any flammable material.
11. If a cell/pack is involved in a crash:
    a. Remove the cell/pack from the model.
    b. Carefully inspect the cell/pack for shorts in the wiring or connections. If in doubt, cut all wires from the cell/pack.
    c. Disassemble the pack.
    d. Inspect cells for dents, cracks and splits. Dispose of damaged cells (see below).
12. Dispose of cells/packs as follows:
    a. Discharge: with the cell/pack in a safe area, connect a moderate resistance across the terminals until the cell/pack is discharged. CAUTION: cell/pack may be hot!
    b. Discard:
       - NiMH: place in regular trash.
       - NiCd: recycle (cadmium is toxic).
       - LiPo: puncture plastic envelope, immerse in salt water for several hours, place in regular trash.
13. Handle all cells/packs with care, as they can deliver high currents if shorted. Shorting by a ring, for example, will remove a finger.
14. Always store cells/packs in a secure location where they cannot be shorted or handled by children.
15. When constructing a pack, use only cells of the same capacity (mAh). During continued use of a pack, periodically check individual cells after discharge and before charging to verify cell voltages are within 0.1V of each other. If a pack has become unbalanced (i.e., cell voltages are more than 0.1V apart), restore balance by charging the cells individually to 4.2V before reconnecting as a pack.
16. Using FMA's Safety Guard voltage limiter while charging series-connected packs is strongly recommended. Note that cells in a pack should still be periodically checked for proper balance.

FMA, Inc. and KOKAM USA, its successors, heirs and assigns are not responsible in any way for any and all bodily injurie(s) and/or property damage that may occur from the use of or caused by in any way the lithium Polymer and NiCd cells/packs stocked and or distributed by FMA, Inc. and KOKAM USA.

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LiPo charging

LiPo cells are charged differently than NiCd/NiMH and all other chemistries except Li Ion. The proper charging schedule limits current to 1C, where C=cell capacity (for example, charging a 145 mAh capacity cell at 145 mA achieves a 1C charge rate). As cell voltage increases, charge voltage must increase to force current through the cell until the voltage applied to the cell reaches a maximum of 4.2 volts. As cell voltage rises to 4.2 volts, current approaches zero. When charge current falls to 0.1 C, the cell is full.

The recommended charge rate is 1C, which charges the cell to 90% capacity in one hour if the charger is designed to hold charge current at 1C without exceeding 4.2 volts per cell maximum charge voltage. Lower charge rates are acceptable if longer charge time is tolerable. LiPo cells **cannot** be charged at high rates such as 4C. Almost nothing is gained by charging at a rate higher than 2C.

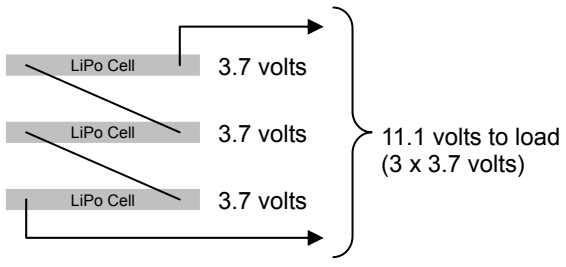
Thus, two important rules govern LiPo charging:

- Never exceed a 2C charge rate, and accept that charging at 1C will maximize cell life.
- Never exceed a maximum charge voltage of 4.2 volts per cell.

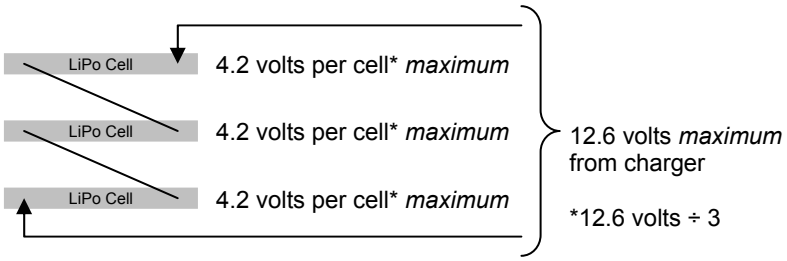
What does “volts per cell” mean?

LiPo cells are often connected in series to achieve higher output voltage. Since a single LiPo cell has a nominal 3.7 volt output, connecting cells in series produces outputs in multiples of 3.7 volts.

A 3s pack, consisting of three LiPo cells connected in series, outputs a nominal 11.1 volts, as shown here:



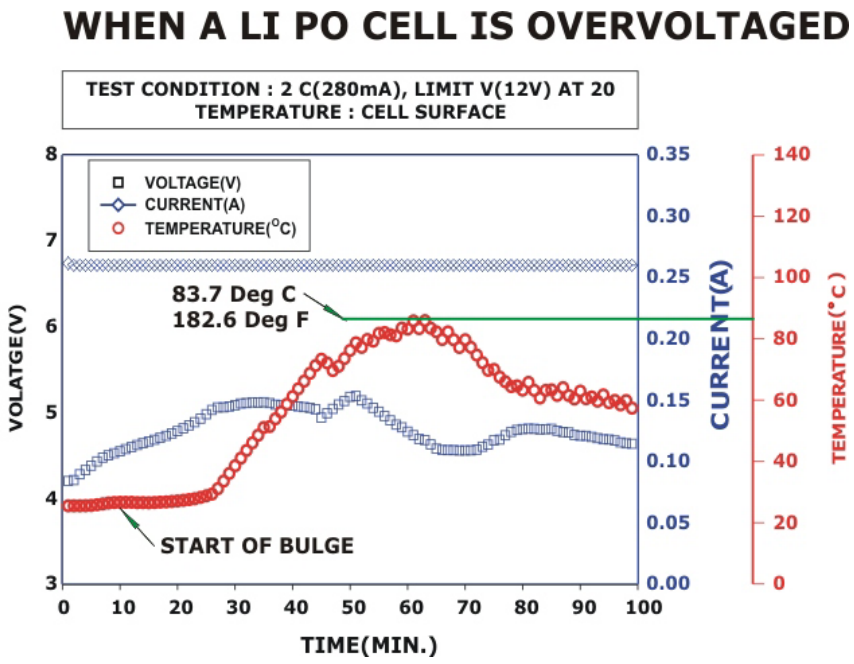
When a series-connected pack is charged, we assume the charge voltage is split evenly among the cells. Thus, when we charge a 3s pack:



Specifying the maximum charge voltage as 4.2 volts *per cell* simplifies the discussion. We can apply that figure to any series-connected pack without knowing the number of cells it contains or the maximum charge voltage the *pack* can tolerate.

Results of overcharging

Under conditions of abuse or error, Lithium cells can vent with flames. During charge, applying a charge voltage of more than six volts per cell for a period of 20 minutes can potentially cause venting and might cause flames depending on current setting.



Charging must be done such that no damage to life or property can occur if a short in wiring or cells, or venting with flames, occurs. All lithium cells have the potential for "venting with flames" if mishandled. This is because lithium is a metal that, under abuse, can ignite and burn.

Lithium ignites in the presence of oxygen. If the cell envelope ruptures, oxygen enters and combines with the lithium, causing ignition. If the cell envelope does not rupture, then ignition will not occur.

LiPo cells, as with any rechargeable battery, react to overcharge. NiCd and NiMH cells react to overcurrent, but LiPo cells react to overvoltage. This is why charging must be carefully limited to 4.2 volts per cell. A LiPo cell has some tolerance for overvoltage; it is not going to balloon and flame unless substantial overvoltage is applied. In the above graph, the charge voltage was set at a very high level—6.8V—right from the start. The cell did not react at all for 10 minutes, then began to swell. A plot of maximum thickness would follow the temperature curve as gasses are generated and heated. Those gasses, for any cell, come from breakdown of the electrolytic as it begins to vaporize. It took almost an hour of overcharge before temperature and pressure rose enough to rupture the envelope.

Safe charging practices

Note: This section supplements "Safety precautions for Lithium Polymer and NiCd cells/packs stocked by FMA Direct," presented in the previous chapter.

In the experiment described in the previous section, the cell under test held out for almost an hour. Leaving any battery on fast charge for an hour without checking it is irresponsible. As stated in the precautions, the cell must be in a safe charging station.

The safety precautions listed earlier include the warning not to charge batteries unattended. If a cell is found to be swelling during charge, remove the charge current immediately. Then allow the cell to cool before taking any other action. If the cell is ruptured, hot gasses and electrolyte could spew out.

Once the cell has cooled, handle it as a fully charged cell with full energy available. This means you do not "poke a hole in it" in preparation for disposal. First, discharge the cell at a reasonable rate. This can be done by using clip leads to attach it to an electric motor, a resistor or some other electrical load. Do not hurry this—a slow, complete discharge to zero volts while still under load is a safe way to do the job. Once the cell is depleted, use a sharp non-conductive object to poke a small hole in the envelope, then immerse the cell in salt water for a few hours. After that, the cell may be disposed of in the trash.

Importance of cell balance

Periodically check the voltage of individual cells in a series-connected pack. All cells should be within 0.1 volt of each other. Unbalanced cells create problems during charging.

Here's what can happen if a pack's cells become unbalanced: you charge the pack, but one cell swells up (which destroys that cell). Of course, *since you are monitoring the charge,* you turn off the charger before the cell vents with flames.

Surprisingly, the swelled cell was not defective before you started the charge. That cell started out with the highest voltage in the pack, and one of the other cells had the lowest voltage. As charging progressed, the cell with the highest voltage was overvoltaged, with the expected result of ballooning. This can happen even if you are using Safety Guard, because Safety Guard only monitors *pack* voltage, not individual *cell* voltage.

If you aren't aware of unbalanced cell behavior, you might remove the swelled cell and build the remaining cells into another pack. Since at least one of those cells is unbalanced on the low side, you will probably destroy another good cell the first time you charge the new pack. This is why it is so important to check individual cells periodically in any pack of any chemistry to make certain that cells are not becoming unbalanced—cells will be damaged if used without being balanced.

Chargers

Chargers designed specifically for LiPo chemistry are available from FMA Direct. Charger specifications may be viewed at the FMA Web site. LiPo-capable chargers are also available from other vendors.

Be extra careful when using a cell-counting charger

Some chargers automatically determine cell count, and this can damage an unprotected pack under certain conditions. An example shows what can happen...

> LiPo cells are nominally 3.7V under load. Cell voltage at full charge is 4.2V. Two fully charged series-connected cells output 8.4V. Three partially discharged series-connected cells may measure 2.8V/cell x 3 = 8.4V. If two nearly charged cells are put on charge to "top them off," the auto-counting charger may incorrectly sense them as three discharged cells and set the charge voltage for three cells. The two cells will receive too much voltage and will definitely be damaged.

Unless the charger you use is known to have a well-designed algorithm for checking the state of charge, you should avoid using that charger in its automatic mode. A 2s Safety Guard connected between the charger and the 2s pack would prevent overvoltage in this example.

By a "well-designed algorithm," we mean that the charger should apply a relatively low current initially, observe the rise in pack voltage and have built-in logic to determine that the rise in pack voltage is very high (for a pack at deep depletion) or very low (for a pack near full charge). In the example above, a 3s pack that is nearly depleted (7.5 V) will show a very rapid voltage rise in the first minute of charge, while a 2s pack near full charge will show almost no voltage change.

Appendix: Safety Guard specifications

FMA Part No.	For pack type*	Nominal pack voltage	Safety Guard voltage limit
LIPOSG-2S	2s	7.4V	8.4V ± 0.1V
LIPOSG-3S	3s	11.1V	12.6V ± 0.15V
LIPOSG-4S	4s	14.8V	16.8V ± 0.2V

*For example, 2s refers to a pack with 2 cells connected in series.

Specifications common to all models	
Maximum input voltage	30VDC
Maximum charge current	20A†
Maximum discharge current	10A
Dimensions (not including leads)	1.06" (27mm) wide 1.4" (35.5mm) long 0.35" (8.5 mm) high

†Note: Safety Guard does not limit current to the pack being charged. While Safety Guard will shut down if current exceeds 20A, it does so to prevent damage to its own circuitry. Excessive charge current will damage or destroy Lithium Polymer cells and packs. In all charging situations, the user is responsible for limiting charge current to 1C, where C = pack capacity (usually stated in mAh or Ah).

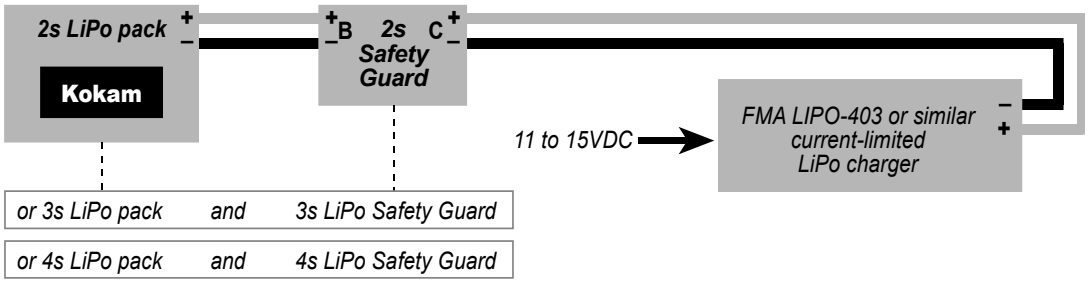
Appendix: Safety Guard applications

Using Safety Guard with a current-regulated Lithium Polymer charger

In this application, Safety Guard prevents accidental overvoltage during charging. The LiPo charger limits current to 1C.

Current-limited LiPo charger requirements:

- Nominal charger output voltage equal to nominal pack voltage.
- Charger output current of 1C or less (where C = pack capacity).

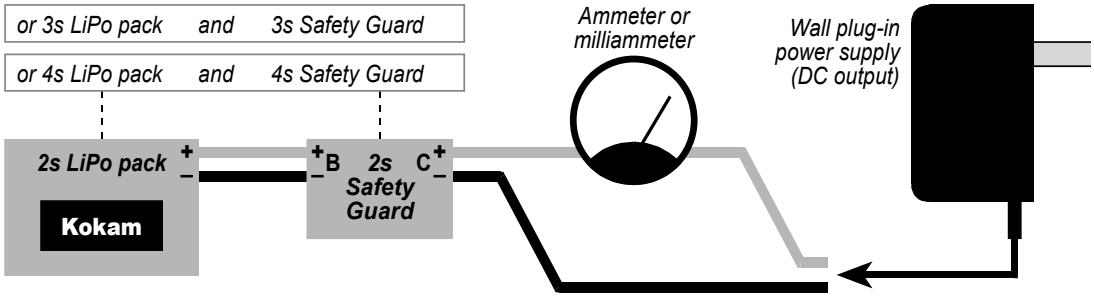


Using Safety Guard with a low current power source

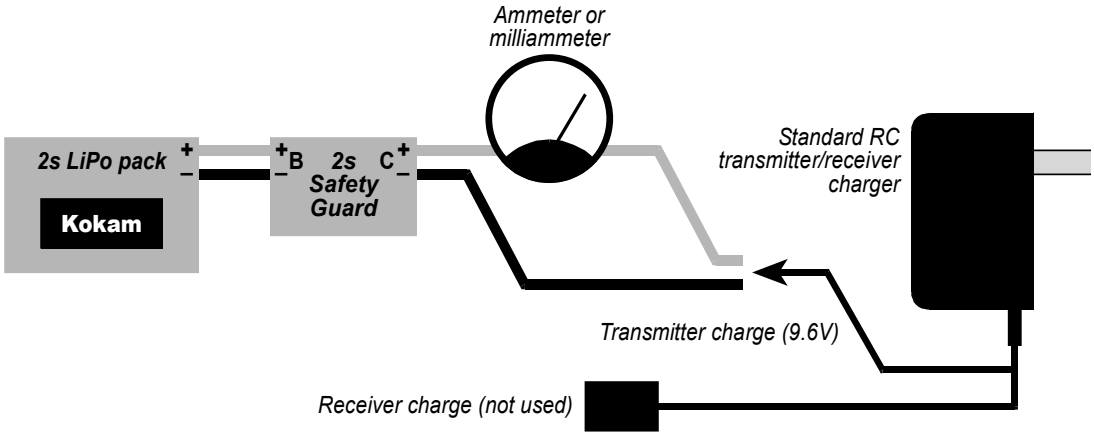
Many wall plug-in DC power supplies have specified output currents in the same range as LiPo charge current limitations. For example, a 12VDC, 1A power supply—when used with a 3s Safety Guard—could be used to charge a 3s (11.1V) 1A LiPo pack at 1C (or a 3s 2A pack at 0.5C, etc.). You must electrically connect the wall plug-in power supply to the Safety Guard by soldering or with appropriate connectors. Monitor pack charging current with a series ammeter or milliammeter to assure it does not exceed 1C.

DC wall plug-in power supply requirements (check supply's label for specifications):

- Output voltage equal to or greater than nominal pack voltage at desired current limit of 1C (maximum power supply output voltage of 30V).
- Specified current of 1C or less (where C = pack capacity).



An RC transmitter/receiver wall plug-in charger, when used with a 2s Safety Guard, can charge 2s LiPo packs. Such chargers deliver 9.6VDC at less than 100mA through the transmitter charge lead, sufficient for charging most 2s LiPo packs at less than 1C.



Using Safety Guard with a high current power source

Typical high current power sources include lead-acid batteries (such as a car battery or field battery) and variable voltage output DC power supplies. **Safety Guard output current must be limited because these sources are capable of supplying currents far exceeding safe levels for LiPo charging.**

If the power supply has fixed output voltage: You must limit pack charging current to 1C or less using a series resistor. Monitor pack charging current with a series ammeter or milliammeter until you determine the resistor value that limits current to 1C or less.

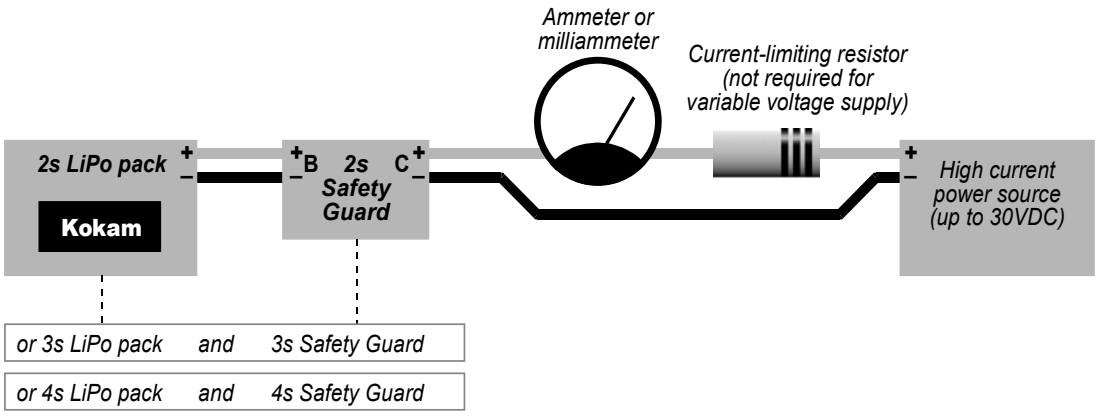
If the power supply has variable output voltage: Monitor pack charging current with a series ammeter or milliammeter. At the beginning of charge, reduce power supply output voltage to limit current flow to 1C or less. As the pack voltage increases, increase output voltage until the power supply regulates voltage at 4.2V per cell.

CAUTION: Do not disconnect the LiPo pack while voltage is applied to it. The sudden decrease in load may cause the power supply to increase voltage before the pack is fully disconnected—and this voltage spike may damage the Safety Guard. Here is the correct procedure for stopping charging:

1. Turn off the power supply.
2. Wait until the power supply's output voltage drops to zero volts.
3. Disconnect the pack from the Safety Guard.

High current power source requirements:

- Output voltage equal to or greater than nominal pack voltage at desired current limit of 1C (maximum power supply output voltage of 30V).
- If power source does not have variable output voltage, Safety Guard output current must be limited by series resistance to 1C or less (where C = pack capacity).



Using Safety Guard with <u>certain</u> NiCd/NiMH fast chargers

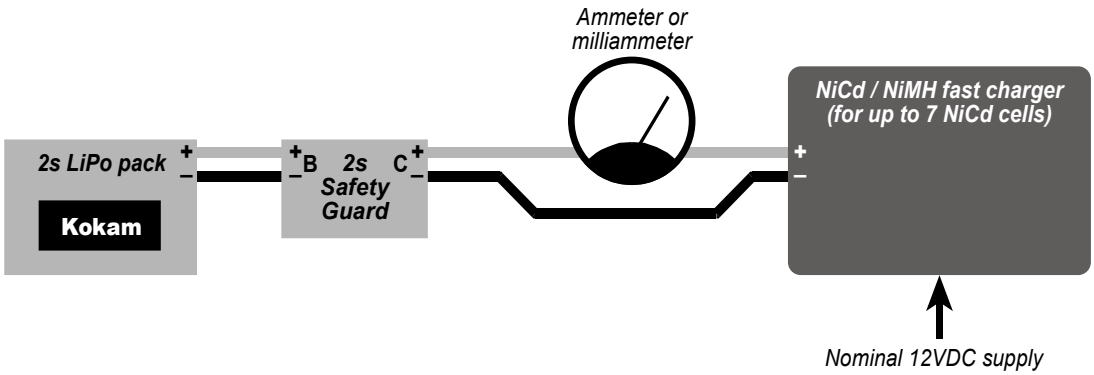
CAUTION: Do not charge LiPo packs with a high cell count fast charger, such as FMA's FC700 Super Nova. When Safety Guard stops the charge, some current may continue to flow. If the charger thinks the pack is still connected, its output voltage may increase, possibly to as high as 50V. If Safety Guard is forced to dissipate high voltage/high current indefinitely, it may fail, which may damage the pack and possibly cause a fire. **If your fast charger can charge packs of more than 7 NiCd/NiMH cells in series, do not use it to charge LiPo packs through Safety Guard.** Such chargers have a DC/DC converter that boosts input voltage from a 12V power source to charge packs with more than 7 cells.

You can charge 2s LiPo packs with Safety Guard and a NiCd/NiMH fast charger rated for 7 cells or less. These fast chargers output constant current, but LiPo packs must be charged with current limiting followed by voltage regulation. The result is that a fast charger will apply too much voltage near the beginning of the charge cycle. Charging this way shouldn't damage the LiPo pack, but the pack won't reach the same charge level as it would with a dedicated LiPo charger. For best results with this arrangement, use a lower current setting. The lower the current, the more charge can be applied to the pack. Safety Guard terminates charging when its output voltage reaches 4.2V per cell.

You *may* be able to charge 3s LiPo packs with a 7-cell NiCd/NiMH charger. 3s LiPo packs require 12.6V input to achieve full charge. Final charge level depends on whether the charger can deliver that voltage when powered from a nominal 12V power source, such as a lead acid battery.

NiCd/NiMH charger requirements:

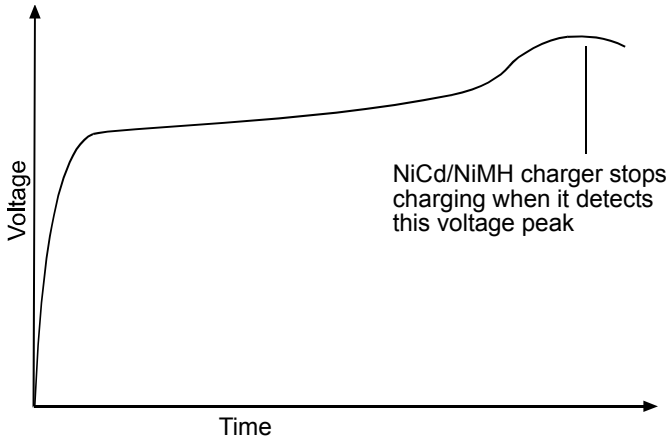
- Fast charger rated for 7 or fewer NiCd/NiMH cells in series (i.e., does *not* have a DC/DC converter for charging 8 or more cells).
- Output current of 1C or less (where C = pack capacity).



Why you can't charge LiPo packs with NiCd/NiMH chargers

The setup described on the previous page shows how to charge a 2s LiPo pack using a 2s Safety Guard and a NiCd/NiMH charger rated for 7 cells or less. **Other than that specific combination, you can't safely charge LiPo packs with NiCd/NiMH chargers.**

NiCd/NiMH chargers output constant current and use peak detection to terminate charging. During a typical charging cycle, charger output voltage follows a predictable pattern associated with NiCd/NiMH chemistry:



Lead acid batteries have similar characteristics. LiPo chemistry doesn't exhibit this voltage peak during charging.

NiCd/NiMH chargers for packs of more than eight cells have output as high as 50 volts. (If powered by a 12 volt source, such chargers use a booster circuit to achieve this voltage.) If you attempt to charge a LiPo pack with this kind of NiCd/NiMH charger, voltage increases toward the charger's maximum because the charger never senses a voltage peak (as it would when charging a NiCd/NiMH pack). Without Safety Guard, this voltage *will* destroy a LiPo pack with dangerous results. Using Safety Guard *might* protect the LiPo pack, but would destroy the Safety Guard. Worst case, both the LiPo pack and Safety Guard would be destroyed.

Using Safety Guard for undervoltage protection

Safety Guard can also be used to monitor pack voltage during discharge. It will disconnect the pack from the current drain if pack voltage drops below 2.5V per cell. Maximum discharge current is 10A.

However, Safety Guard is not practical for controlling undervoltage in many RC applications, as it will completely disconnect voltage to the device being powered by a LiPo pack. Also, many RC applications exceed Safety Guard's 10A discharge rating. A Speed 400 motor, for example, draws up to 12A when powering an electric aircraft.