# Electric Vehicle Safety

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## Two general areas of concern:

1. Safety issues related to the battery and high-voltage/high-current wiring and systems on the vehicle
2. Related to other attributes of battery-electric vehicle operation and service

## Battery-related safety issues

Most student-built or home-built EV conversion projects use lead-acid batteries. Despite the development of much more advanced batteries, the cost per energy storage accessible over the life of the battery ($/kWH-cycles) still remains (2011) the lowest of all rechargeable battery chemistries.[2] Lead-acid batteries are also tolerant of abuse and almost 100% recyclable. The great disadvantage of lead-acid is energy density (kWh/kg), which limits vehicle range.

Since we are using lead-acid batteries for all of our vehicle projects, I will discuss EV safety issues related to batteries only in the context of lead-acid batteries. Advanced batteries such as lithium-based chemistries have their own unique safety issues, which could not be discussed comprehensively here.

## Basic types of Lead-acid Batteries

**Flooded** – The least expensive per kWh, and most common automotive lead-acid battery. Each of the 6 cells in a 12 Volt battery can be accessed, allowing checking electrolyte levels and "watering" the battery. Cells are vented to the atmosphere to relieve pressure created by the generation of hydrogen and oxygen due to electrolysis of the electrolyte.

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[2] Author's calculations based upon published lowest production cost of $500/kWh for Li-ion batteries vs $75/kWh retail cost for Grp 27 deep cycle batteries purchased locally. Lifetime charge cycles: 1000 for Li, 300 for Pb-H2SO4.

**AGM (Absorbed Glass Mat)** – A Sealed or Maintenance-Free battery. The first of two types of Valve-Regulated Lead Acid (VRLA) batteries, meaning that they allow some pressure to build up in the battery (typically 1-4 psi), up to the limit of a pressure relief valve, and do not allow air to enter the battery. Essentially the same as a flooded battery, except that electrolyte is held in a paste retained by fiberglass mats in contact with the lead or lead-alloy plates. More accurately classified as "Recombinant Gas" batteries, meaning that the hydrogen and oxygen generated due to charging is recombined in the electrolyte paste, forming water again. Big advantage is no need to periodically water the batteries. Cost is higher than flooded batteries, and AGM batteries cannot tolerate even a single overcharge cycle. The well-known Optima "Tubular Cell" battery is a type of AGM battery.

**Gelled Electrolyte (or Gel Cell)** – Another type of recombinant gas VRLA battery, but using a gel electrolyte, typically sulfuric acid mixed with silica fume , which fills the space between the (usually sponge-lead) plates. Attributes similar to AGM batteries. Need not be kept upright. Standard type of battery for UPS computer power systems and consumer products which use do not require the higher energy density of an advanced battery.

**Within each type, three *purpose designations* have become standard**

**SLI (Starting Lighting and Ignition) –** An automotive starting battery. Designed to produce high current for short periods by maximizing active plate surface area, and minimizing plate separation. Will not last long if deep-cycled, since thin fragile plates will be quickly destroyed.

**Deep Cycle** – Thicker, usually solid plates with less surface area allow these batteries to be almost fully (down to 20%) discharged without permanent damage. Less power, but greater *usable* energy than SLI batteries. These are the batteries used in almost all EV's which use lead-acid batteries.

**Marine Deep Cycle** – Half-way between a true deep cycle and an SLI battery, since they are used to provide continuous power for electrical loads on watercraft, but must also be able to provide short bursts of high current to start a marine (usually a diesel) engine.

*The most common battery used for converted electric vehicles is the* ***flooded deep cycle battery****. This is because the cost is the lowest, the energy density (kWh/kg) is the highest, and the ability to service the battery electrolyte level is important to maximizing the life of the battery. In all material that follows, flooded lead-acid batteries will be assumed, although the recommendations are generally applicable to all lead-acid batteries.*

## EV Battery Voltage and Current Considerations

### Electrocution hazard:

What voltage is dangerous? If current is not limited to a very small value…

The U.S. National Electric Code (NEC) NFPA 7OE, for example, Par. 1 10.7(F) sets threshold of safety at 50 volts.

IEEE Specification TS-60479-1 suggest that these longstanding limits are too high.

OSHA: safe "touch voltage" voltage limit set as low as 35 Volts in the USA, and 24-25 Volts in European countries. The Canadian Electrical Code defines "extra low voltage" as "up to and including 30 volts" and national health and safety regulations consider that voltage as the worker safety threshold.

International Electrotechnical Commission Specification IEC 60479-5 the IEC (European Standard) states: body contact between 36 and 49 volts could cause ventricular fibrillation; recommends safe limit between 25 and 30V.

**Example: Batteries in our GM/Conceptor Electric G-Van:**

> Original with 6V to 12 V battery conversion done by Art: Two strings of 18 12-volt Group 27 deep-cycle batteries in series: 216 volts nominal (227 volts fully charged, disconnected from charger)
>
> Typical HCA (Hot Cranking Amps) rating of one Grp 27 Deep-cycle 12 battery: 1200 amps, pulse discharge as high as 1700 amps.
>
> 227 x 1700 amps x 2 strings in parallel = 772 kW pulse power (or 386kW for the RBX battery pack)
>
> G-Van battery charger (large green): output 270 VDC @ 50 Amps = 13.5kW
>
> Each of the three small black chargers: output 90 VDC @ 20 Amps = 1.8kW
>
> For comparison – residential 115 VAC (RMS) outlet with 15A circuit breaker: 1.7kW

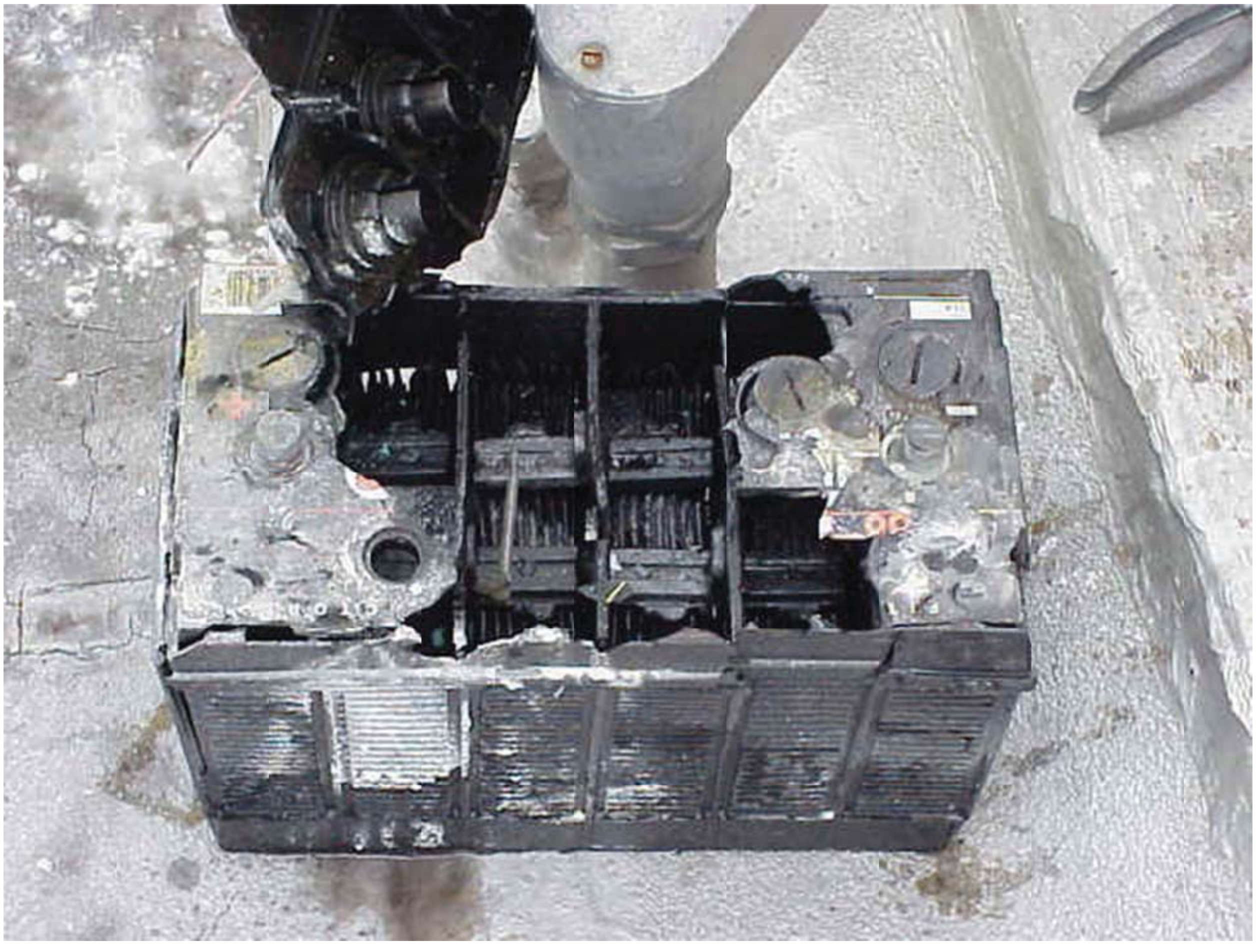
**Electrical burns:**

Electrical hazards are not limited to potential electrocution – a wrench across the terminals of an EV battery pack can vaporize like a fuse. If held in your hand, it will take your hand with it. Even a single 12 Volt automotive battery can cause serious burns if your skin is in contact with a conductor that short-circuits the battery. http://www.youtube.com/watch?NR=1&v=j25dh7w48Xs

**Battery explosion:**

When overcharged, a lead-acid battery will produce hydrogen gas and oxygen gas by electrolysis of the acid/water electrolyte. This naturally occurs in the final stages of a full charge cycle. If the rate of overcharge is small, the small amount of gas will be dissipated harmlessly. However, if overcharged or if ventilation is inadequate, especially as the gas space in the battery increases as electrolyte is lost, a flammable concentration of hydrogen will remain in the cell. An internal spark, e.g., due to a high-discharge-current burst upon vehicle acceleration, can cause a hydrogen/oxygen explosion, which will usually rupture the case and disperse acid into the surroundings. Anyone close to the battery may be injured. If charging in an enclosed area, or batteries are located in the interior of a closed vehicle, ventilation is required to keep hydrogen concentration below 1%.

*Battery explosions in EV's are far more common than most people assume*. It typically occurs when one or a few battery(ies) in a long series string of many batteries (like the G-Van) is bad, while the remaining batteries in the string are good. Charging the series string exhausts the remaining electrolyte in the bad battery(ies). The first time the vehicle is operated, high current flows through the string, causing an failure of the internal conductors or the fuse-like vaporization of an inter-cell dendrite bridge. This ignites the mostly gas-filled battery, causing the rupture of the case.



An Exploded 12V SLI Battery,

(from http://www.rayvaughan.com/battery_safety.htm )

How to reduce the risk of EV battery explosion? Check each battery in the string individually with a hygrometer and/or voltmeter. Remove bad or weak batteries from the string. Make sure that all batteries in the series string are in approximately the same condition. ***Don't mix new with old batteries***!

**Acid burns:**

Acid splash or spill can result from battery explosion as previously mentioned, or during battery watering or initial electrolyte filling. Will also occur if a battery is dropped and the case is ruptured.

Battery electrolyte is concentrated sulfuric acid. Can cause chemical burns on skin or blindness if in contact with eyes. Inhalation of acid vapor or mist can cause respiratory damage, but fortunately, sulfuric acid is not a highly volatile liquid (compared with organic solvents like gasoline).

Always wear acid-proof gloves nitrile (not leather or fabric) gloves, and wear full-eye-coverage goggles when servicing batteries. Work in a well-ventilated area.

**Maintenance and charging considerations:**

Voltage and current depend on the battery pack configuration. For a single 12V Deep-Cycle flooded Lead-acid battery of any size:

| Open circuit voltage | | Approximate charge | Relative acid density |
|---|---|---|---|
| **12 V** | **6 V** | | |
| 12.65 V | 6.32 V | 100% | 1.265 g/cm$^3$ |
| 12.45 V | 6.22 V | 75% | 1.225 g/cm$^3$ |
| 12.24 V | 6.12 V | 50% | 1.190 g/cm$^3$ |
| 12.06 V | 6.03 V | 25% | 1.155 g/cm$^3$ |
| 11.89 V | 6.00 V | 0% | 1.120 g/cm$^3$ |

This table was copied from http://en.wikipedia.org/wiki/Automotive_battery but the data may be found in almost any reference on lead-acid batteries.

- Quiescent (open-circuit) voltage of a fully-charged battery after a few hours: 12.6 V
- Open-circuit voltage of a fully-discharged battery: 11.8 V
- Charging voltage range: 13.2–14.4 V. Gassing voltage: 14.4 V. Continuous-preservation charge voltage (max) 13.2 V
- Smart chargers schedule the charging voltage to store the maximum amount of energy in the battery without degrading its life (much).
- Charging to 100% capacity requires a final gassing phase, in which some electrolyte is lost to electrolysis. This necessitates more frequent battery watering.
- Battery Voltages are temperature-dependent. Each cell (nominally 2.1 volts at 68 deg F.) has a positive temperature coefficient of approximately 3.3 mV/deg F., or 20 mV/deg F. for a 6-cell 12 V battery.

- Most automotive voltage regulators are set to charge the 12V battery at slightly above 14 Volts.
- After a full charge the terminal voltage will drop quickly to 13.2 V and then slowly to 12.6 V. This is due to the surface charge (also called space charge) which adds to the battery voltage, but contributes almost no usable energy capacity. It will dissipate naturally, so wait at least an hour, and ideally 12 hours, to get a reliable open-circuit voltage measurement. If you need to assess the battery immediately, the next best method is to slightly discharge the battery, say, by driving the electric vehicle about 30 seconds.
- A resistive battery load tester will provide a good indication of the battery health, even if done shortly after charging. This draws heavy current from the battery for a few seconds and measures the voltage under load. Note that commercially-available load testers work only on individual 12V batteries – they do NOT work on a series string of batteries as found in an EV; the load tester will fail catastrophically if used on anything other than a 12V battery.

Charging current depends on the size of the battery and the phase of the charging cycle. Current should be monitored to confirm charging, but it is the charging voltage that is usually the primary control variable. Charging voltages at or above 2.4 V/cell or 14.4 volts for a 12V battery will cause “gassing” and loss of electrolyte. As electrolyte is electrolyzed and vented, the current density in the remaining acid and on the remaining plate surfaces increases, accelerating the loss process and unevenly re-plating the lead electrodes. Charging voltages above 15V will eventually destroy a lead-acid battery due to this process.

**Typical causes of lead-acid battery failure:**

- Sulfation causing an insulating coating of active plate surfaces and loss of active materials (lead and sulfuric acid)
- Erosion/corrosion failure of plates
- Inadequate electrolyte level
- Shorted cell or cells due to failure of separators, build-up of spalled plate material below the plates of the cell, or lead dendrite growth between plates
- Internal physical damage: Broken internal inter-cell or terminal connections
- External physical damage: Cracked or broken case or terminals

These conditions can be the result of overcharging, leaving a battery in a discharged state for a long time, failing to water a battery with a low electrolyte level, or physical damage (e.g., drop or vibration). But a lead-acid battery will wear out eventually even it is well-cared-for.

**Why do batteries eventually wear out, even if not abused?**

**Battery Sulfation:**

Sulfation is the formation of lead sulfate by combination of lead and sulfuric acid. It takes the form of large, non-conductive crystals formed on the plates, which eventually precipitate to the bottom of the battery case. Once sulfate is formed, it is impossible to reverse (although many battery additives claim otherwise). In the discharged condition, both lead plate material and electrolyte acid are lost to the sulfate, and the crystals adhering to the plates reduces the current-carrying surface area, reducing the power output as well as the energy capacity of the battery. It occurs naturally with time, but is greatly accelerated when a battery is not fully charged. The longer it remains in a discharged state the more permanent damage is done, and less useful capacity of the battery. Sulfation can be greatly reduced by maintenance (trickle) charging, typically a 12.7 volts and a maximum of 1 Amp. Do not leave lead-acid EV batteries in a discharged state any longer than necessary. Start charging immediately after a day’s driving.

**Erosion of plates:**

With successive charge-discharge cycles, active material is spalled (shed) from the battery plates, which accumulates at the bottom of the cells.

**Plate deformation after many charge-discharge cycles:**

Also with successive cycling, lead is not evenly re-deposited on the plates. The surfaces becomes increasingly deformed. High points (dendrites or lead bridges) may eventually form between the plates which will cause the internal short-circuit of an individual cell. This is more likely with SLI batteries than with deep-cycle batteries, due to the narrower plate separation.

**Corrosion at the battery terminals and connectors:**

The white powder sometimes found around the battery terminals is the same lead sulfate found inside the battery if poorly maintained.  It is toxic but not terribly dangerous, just don't breathe the dust and wash it off your hands. This form of corrosion is usually caused by an imperfect seal between the battery case and the battery posts, allowing sulfuric acid to react with the lead battery posts. Battery terminal "protection sprays" contain sealants that help to reduce acid weeping past the terminal posts, as well as coating the terminals to prevent contact with leaked acid.

The corrosion process is expedited by overcharging.  Corrosion can also be caused or made worse by salt water, dirt, heat, humidity, cracks in the battery casing or loose battery terminals. Inspection, cleaning and protection with a light coating of dielectric grease or terminal protection spray can significantly reduce corrosion of battery terminals.

## General electrical hazards while working on EV's

**Inattentiveness or carelessness is the greatest cause of accident or injury:**

"Cal Poly and MIT students destroy motor controllers"

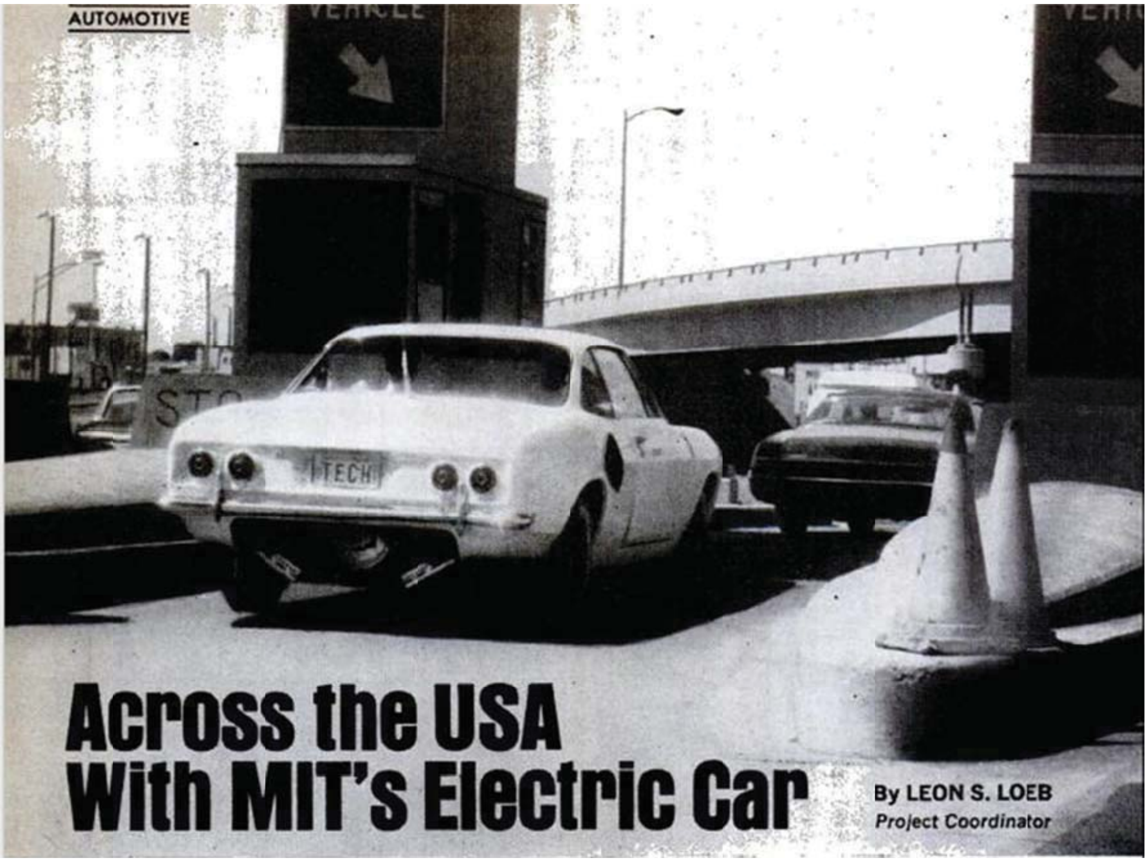
Cal Poly:

2000: EVEC students working unsupervised on the RX7 race car incorrectly connected a new $1200 Zilla controller. They neglected to thoroughly study the manual, or to consult with their adviser. When activated, the car accelerated at maximum power in reverse into the side of the EE Building. Fortunately, no one was injured, although the car was damaged and the controller destroyed.

MIT:

1968: During the 1968 Great Transcontinental Electric Car Race between Caltech and MIT, the Caltech-converted 1958 VW microbus won (by only 30 minutes) over the MIT-converted 1968 Corvair, which on the last day of the race was in the lead and not far from the finish line in Pasadena. This occurred because a member of the MIT team incorrectly connected their charger which burned up the motor controller. Their car was towed across the finish line. The Caltech entry ran on Lead-Cobalt batteries costing about $2,000. The MIT entry ran on NiCad batteries costing about $20,000. Both vehicles carried less than 2 kW of energy onboard.

(Photos and historical credit: MIT car from Popular Mechanics, July, 1968. Caltech from A.E.V.Co. Motors web site accessed November 2011. http://www.aevcomotors.com/index.php?main_page=document_general_info ).



AUTOMOTIVE

# Across the USA With MIT's Electric Car

By LEON S. LOEB
*Project Coordinator*

***When working on electric vehicle power wiring or connections, keep your focus, do not allow any distractions. Wear insulating gloves and protective goggles. Remember the One-Hand Rule. Never work alone. Have a safety-buddy with you who is ready at any moment to help you, and knows how to help you.***

**If a battery-related accident in the lab occurs:**

- If the person is still connected to a high-voltage electrical source, get them away from it *without touching them*.
- Check for pulse and breathing. Administer CPR and/or rescue breathing if necessary.
- Call 911. Yell for help.
- If acid splash, wash with lots of water ASAP. Be sure water does not get near the batteries or electrical source. Use eye-wash station if nearby. Baking soda has little value on a person after acid contact with skin or clothes. Get immediate medical attention if severe.
- If electrical burns, also treat with cold water ASAP, again, keeping water away from the voltage source. Get immediate medical attention.
- Most acid contact is not severe – just wash it off your skin immediately (don’t wait, you won’t feel it at first).
- Acid on clothing – remove clothing as soon as feasible, and wash with water. Battery acid will easily eat a hole in cotton or most natural fabrics, often well after the initial contact, if it has not been washed out right away. Note the holes in the jeans of people that work on batteries frequently.

## Some EV Design Safety Precautions

- Neither side of an EV traction battery is ever connected to the vehicle chassis. Both the positive and negative power circuits are isolated.
- The battery/motor/controller system must have at least one expendable fuse in ***each*** leg from the battery (note the dual fuse box in the G-Van).
- A manually-actuated contactor must be provided which breaks both connections to the battery.
- Battery enclosure must be well-ventilated, usually outside the vehicle cabin. Note that the RX7 does not have closable windows.
- The battery enclosure must be separated from the driver and passengers in such a way as to contain the explosion of multiple batteries.
- The added vehicle mass due to batteries and motor, less the weight reduction from the IC engine removal, must remain at least 800 lbs less than the GVWR for a 4-passenger vehicle. If the GVWR is exceeded with driver, passengers and cargo onboard, the safety of the vehicle depends on the original safety margin used in the design of the **brakes, suspension, and steering systems.** (This is frequently violated in home-built conversions).
- Any electric vehicle offered for sale to the public in significant quantities must meet the same crash safety regulations as an IC engine vehicle. http://www.nhtsa.dot.gov/cars/rules/import/fmvss/index.html . Most limited-production EVs based upon originally-certified IC vehicle chasses are allowed under an FMVSS low-production/experimental exemption.
- Silent electric propulsion leads to an increased risk of collision with pedestrians at slow speeds. Under the Federal "Pedestrian Safety Act of 2010" http://www.govtrack.us/congress/bill.xpd?bill=s111-841 , a battery-electric vehicle must include some audible device to warn pedestrians when operating at very slow speeds, turning or backing up.
- Careful routing of power wiring to avoid abrasion, deflection of cables under high current.
- Use double barriers to contact with power-carrying conductors – insulation on cables and connectors, inside secure enclosures.

- Sweat the details. Sloppy or poorly-thought-through work leads to dangerous situations for which the engineer is liable.

## Many online resources, training references and case histories, e.g.,

A good general online reference for lead acid battery data:
http://www.hupsolarone.com/about-batteries.htm

Online reference on battery types and purpose-classifications is:
http://www.windsun.com/Batteries/Battery_FAQ.htm#Major%20Battery%20Types

First responder training:
http://www.greencarreports.com/news/1045798_facing-a-wrecked-electric-vehicle-what-must-ems-staff-know

Chevy Volt battery mounting issues and fires:
http://www.greencarreports.com/news/1068533_third-fire-consumes-a-chevy-volt-electric-car-perspective

GM's free (really slick) accident response training for Volt:
http://nfpaevresources.gvpi.net/

Results of DOE Study on Lead-acid Battery Safety from LLNL:
www.lanl.gov/safety/electrical/docs/battery_safety.ppt

Example of a badly-built commercially-sold EV:
http://www.blyon.com/tag/hybrid-technologies/

Off-beat but apropos shop regulations and project team management:
http://www.youtube.com/watch?v=49p1JVLHUos&feature=relmfu

**References –** Most material presented above is from the author's personal experience or general knowledge, but all photos, some data and recommendations were taken from standard reference sources or non-copyrighted web sites (citations in text). This presentation is not comprehensive. It is a concise summary for the benefit of students working on EV projects.