Understanding Lithium Batteries

Kathy and Reg Nicoson of EarthX, Inc. explain what you need to know.

BY JARED YATES

Kathy, Shane, and Reg Nicoson in the EarthX booth at AirVenture.

"Lithium batteries...those are the ones that explode, right?" Kathy Nicoson, global sales director for EarthX, Inc., says this is the question she hears the most. Even though she's heard it a thousand times, if you ask her this short question, she will smile kindly and provide as long of an answer as you would like to receive.

EarthX is a Colorado-based company that has sold tens of thousands of lithium batteries in the motorcycle and powersports industry since 2009, and has sold thousands of their aviation-specific battery since 2015. As Kathy points out, EarthX batteries were being installed in airplanes long before EarthX sold an aviation-specific battery. It didn't take long for builders of Experimental/Amateur-Built airplanes to see the lightweight appeal of lithium batteries available for powersports applications, and they have been installing them in aircraft for years.

Reg (rhymes with "hedge") Nicoson is an electrical engineer with 20 years of experience in product development at General Electric. He and another partner founded EarthX, where Reg is lead product engineer. Upon realizing that his motorcycle battery was going into airplanes, he set to work developing an improved version, with expanded protection circuitry and capacity.

Reg originally got into the business of making motorcycle batteries back in 2008 by first making one for personal use. His fellow motorcyclists were impressed, so he started building packs for them, too. Those beginnings grew into EarthX, and before long their batteries were running in all sorts of powersports equipment. In that market, price is often more important than safety. The results of battery failure are not usually catastrophic for a ground vehicle, but obviously aviators weigh the risks of failure differently. That leaves room in the market for an aviation-specific battery that costs a little more, but has even more safety features.

Recently, Reg and Kathy gave me a tour of their assembly plant in Windsor, Colorado, explaining how they make their batteries and what makes their batteries different from the others available. But to understand what those safety features are, or why they are necessary, we must first take a short detour that will pass through the sometimes murky world of peer-to-peer information sharing.

A builder considering the switch to lithium batteries is only a Google search away from hundreds of pages of misinformation, especially on message boards and builder communities. Discussions often start with a brave soul who dares to suggest that he might like to save a dozen pounds by installing one. Early on, someone will reply about Boeing 787 headlines. Soon thereafter, an expert who has experience with lithium batteries in model airplanes will tell everything there is to know about his LiPo (lithium-ion polymer) battery. There also will be a post or two about how often consumer electronics like cell phones and laptops fail in catastrophic balls of shooting fire, bringing down airliners and destroying the hopes and dreams of people everywhere.

Somewhere in a sea of threads like these float small islands of intelligent discussion about the merits and pitfalls of lithium batteries, but it sure can be hard to find those islands. Hopefully this piece will help navigate the discussion, but realize that there is much more to the topic than can be fit into a short article.

Size matters: The Concorde lead acid battery measures 7.50x4.57x6.81 inches and weighs 23.5 pounds. It was replaced by an EarthX ETX680C, which measures 5.9x3.4x4.5 inches and weighs 3.9 pounds, a weight savings of 19.6 pounds.

Lithium Battery Basics

Lithium batteries are widely misunderstood in part because the term "lithium battery" is too general, and people gravitate to the failures of lithium batteries without realizing that there are different types of lithium batteries. It is also common for us to compare lithium batteries with a non-existent ideal alternative, instead of the best alternative that is actually available, overlooking the risk associated with any kind of energy storage. We must realize that lithium batteries are literally everywhere. Passengers routinely board commercial airplanes, each with perhaps half a dozen of them in their carry-on luggage and on their body. Those airplanes, including the 787 with its own lithium ship battery, fly over our heads every hour of every day, and while they do occasionally encounter problems, the problems are extraordinarily rare. When the 787 was initially designed, LCO (lithium cobalt oxide) batteries were the only technology available. The systems had some initial failures, including two thermal runaways, but over 500 787s have been flying around the world since then with reliable performance, even with the less-forgiving LCO chemistry. When we understand how widely used lithium batteries of all types are, we see that the failure rate is very low—but it is still easy to focus on the rare failures and forget how huge the sample size really is.

It is also easy for us to be complacent about energy storage because it happens all around us every day. Powered airplanes have some type of energy storage, often gasoline, and most of them also have storage for electrical energy. If that energy is rapidly released ahead of schedule, the results are unfavorable. The diminutive AA cells in an ANR headset can be made to start a fire, but we don't think of them as exploding batteries. A battery capable of starting an airplane engine is capable of spraying a shower of sparks when shorted directly, a lesson quickly learned and long remembered by the unfortunate mechanic that somehow shorts one. Lead-acid batteries can, and do, explode. The old unsealed types can vent hydrogen during normal use, which burns and explodes violently. All lead-acid batteries (wet, gel, AGM) can still explode and vent hazardous gases and acid.

If stored energy is always a source of risk, why do lithium batteries get such a bad rap? Generally speaking, lithium-based cells are able to deliver a lot of energy quickly, and they are not forgiving

Photos: Jared Yates

to mistreatment while charging and discharging. If the cells are treated in a way that causes their temperature to rise sufficiently, the internal parts start to fail, and the battery can short internally, further increasing the cell's temperature. If it gets bad enough, this thermal runaway will cause a failure of the pack. Thermal runaway is not a condition unique to lithium packs; it can also occur with AGM batteries (like the popular Odyssey series) and the NiMH (nickel-metal hydride) packs used in larger airplanes. Perhaps lithium batteries are an easy scapegoat because they are relatively new.

It is important to understand that there are many different kinds of lithium batteries, with at least half a dozen widespread varieties that are loosely called "rechargeable lithium-ion." Each flavor of lithium battery has its own cocktail of characteristics such as its cell voltage, tolerance to physical and electrical abuse, physical shape, production cost, and failure mode.

LFP Batteries

When it comes to making a lithium battery for starting engines like ours, there is only one type of lithium battery that is viable: the lithium iron phosphate (sometimes abbreviated $LiFePo_4$, or LFP). This is not the same cell as the more common lithium cobalt oxide ($LiCoO_2$, or LCO), which is used in applications like the Boeing 787 and the LiPo packs in flying models. The LCO is ubiquitous in small consumer electronics like phones and computers. Adding to the confusion, the specific term "lithium iron" looks and sounds very similar to the general term "lithium-ion." Familiar brands of LFP batteries marketed for motorcycle and powersports use include Antigravity, Ballistic, EarthX, Full Spectrum, Bike Master, WPS, and Shorai.

The LFP is well suited for vehicle systems because it is the most abuse-tolerant type in widespread use. The temperature required to reach thermal runaway is 518° F, compared to 302° F for the LCO. If the LFP pack does actually reach thermal runaway, its failure mode is much less dramatic than the LCO. In the worst case, LFP packs can vent electrolyte and smoke for several minutes, but they do not vent flames like the LCO. When an educated lithium battery user sees the sensational news headline of a catastrophic failure or a fire created by an exploding lithium cell, it is wise to wonder what kind of cell was in use and realize that it was almost certainly not the LFP type.

If the LFP is so safe, why is it not used in all battery-powered devices? One answer is in the LFP's lower cell voltage, which can be a big disadvantage in something like a mobile phone. For vehicle applications, this disadvantage actually works in our favor, and here's why: Traditional lead-acid batteries operate at 2 volts per cell. Most E/A-B airplanes use 12-volt batteries that have six internal cells, with charging systems delivering around 14 volts. The voltage of the charging system must be higher than the voltage of the battery in order to charge the battery. LFP cells operate between 3.2 and 3.6 volts per cell. With four cells in series, that gives a voltage range of 12.8 volts to 14.4 volts, which works out quite nicely with existing vehicle charging systems. Compare that to the much more common LCO cells, which in a 4-cell configuration would have a voltage range of 14.4 to 16.8 volts. This range is too high, which means that the battery would not be charged without a redesign of our charging and starting systems. For most of us this would be, shall we say, a non-starter.

Advantages and Disadvantages

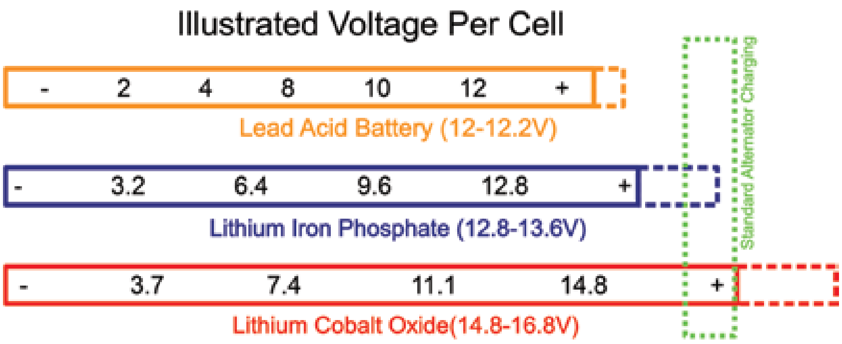
So let's summarize the advantages of a battery made with LFP cells. First, the weight reduction over lead-acid is dramatic. The exact comparison will vary, but rounding conservatively, the lithium battery will save 10+ pounds, perhaps as much as 80% less than the

Overvoltage Protection

Builders must be able to read the documentation and understand the limitations of a battery with an on-board battery management system (BMS). For example, consider overvoltage protection. Some E/A-B airplanes use an automotive style internally-regulated alternator. It is possible for those regulators to fail in such a way that drives the field current up, which causes the alternator to deliver its maximum output. Builders have known about this for years, and most have incorporated some means of absolute field control, along with crowbar overvoltage protection. If these terms sound foreign, there is much more detail in Bob Nuckolls's book, *The AeroElectric Connection*, and his associated email list.

The Plane-Power brand of alternators are examples of internally-regulated alternators that also provide for absolute field control. In a case where the alternator fails to this overvoltage condition, a traditional lead-acid battery will likely accept enough of that electrical energy to keep the bus voltage in the 25–30 volt range for several minutes. However, the EarthX aircraft BMS will block off incoming current to the battery to protect the cells after just one second. If there is no crowbar overvoltage protection to automatically disconnect the alternator within that one-second window, once the EarthX BMS isolates the battery, the bus voltage will spike, and sensitive electronics could be damaged. Once bus voltage is sustained above 60 volts, the internal MOSFETS (metal oxide semiconductor field effect transistor) on the EarthX BMS may no longer be capable of maintaining protection. Some engines like the Rotax 912 are only capable of putting out 40 volts in their worst-case overvoltage condition, so not all aircraft charging systems need an automatic overvoltage protection circuit. EarthX provides a flow chart to help customers decide these points.

There have been three known cases of EarthX batteries failing in overvoltage conditions, though each time there were several contributing factors beyond the battery. In one case, the aircraft had an electrically-dependent engine, an internally-regulated alternator, and no overvoltage protection. The regulator failed and drove the bus to 100 volts, which also happened to coincide with a powersports version of the battery having a bad cell. There were indications prior to



Lithium cobalt cells are not well suited for vehicle applications, especially because of their voltage. Voltage is too high with four cells and too low with three. Lithium iron phosphate cells naturally have a lower voltage, making a four cell pack ideal for alternator charging.

lead-acid battery it is replacing. The slightly higher voltage of the LFP pack will turn the prop 20% faster during the engine start. The self-discharge rate is much lower, meaning the lithium battery will hold more of its charge during a long break between flights or during an off season. The operating and exposure temperature limits are also a little less restrictive on lithium batteries. LPV (linear parameter-varying) cells are much more vibration tolerant than lead-acid cells, which count on the mechanical attachments of structurally-weak lead plates. This is one reason why the life span in service of the lithium cells is planned at 5–8 years, compared to 1–4 years for a lead-acid battery. Compared to an old flooded lead-acid battery, there is no risk of acid leakage and no need to mount the battery upright, though few E/A-B operators are using these kinds of batteries anymore.

Those are some of the benefits, but what about the drawbacks? First and foremost, the LFP battery is less tolerant to abusive charge and discharge practices. This leaves two options. Either the packs must be regulated by a sophisticated battery management system (BMS), or the end user must be willing to accept the risks of not having that protection. There are builders who install one of the powersports batteries that are not recommended for use in airplanes by their manufacturers, demonstrating a spectrum of risk tolerance. The various manufacturers approach this situation in different ways, and as Kathy from EarthX points out, the term BMS can be a general term applied loosely. Builders who see lithium batteries as all pretty much the same should look first at the BMS capabilities.

The first level of protection is cell balancing. Cell balancing is a simple part of the BMS and can be handled by a very inexpensive circuit. The next level up is with overvoltage protection, which is a little more difficult and expensive to incorporate. Lithium battery manufacturer Aerolithium advertises that their BMS does not include overvoltage protection or overdischarge protection, and says this is by design. They say it is best to allow the pilot to extract the maximum energy available from the battery in case of an electrical emergency, though doing so will inflict permanent internal damage to the battery.

For most operators, an overdischarge situation is going to arise not on the way to a landing, but after leaving the plane in the hangar with the master switch on. The EarthX overdischarge protection is designed to allow three months with the master on without damaging the battery. In other words, someone could leave the master switch on for as long as three months, then come back to the hangar and charge the battery without long-term damage.

As of this writing, Aerovoltz, another lithium battery manufacturer, lists no

the incident flight that the cell was failing, including reduced cranking ability. The aircraft had no backup alternator or battery, and all of the engine's critical electrical functions were on a single bus. After a sustained period above the 60-volt protection limit, the weak cell ruptured, and the aircraft was left without any power supply. The engine lost power and the subsequent forced landing damaged the aircraft (cracked the windshield), but thankfully the pilot was unhurt.

There were two other cases that were very similar to each other. In both cases, a failed internal regulator created an overvoltage condition. In both cases the electrical systems sustained very high voltage for several minutes, and the pilots took no action to disable the alternator or even to turn off the master switch. Both pilots landed off airport when the battery finally ruptured a cell and began smoking. The fault indicator in the battery was not connected to a cockpit display in either case, and it would have indicated a problem if it had been. It is fair to say that these kinds of conditions are going to create major problems in any electrical system, regardless of the battery chemistry. These cases underscore how important it is to have automatic overvoltage protection, especially in systems that will use a lithium battery.

The final known case of a failed EarthX battery in an aircraft is documented in a thread at *www.avidfoxflyers.com.* This case was not due to overvoltage. The builder installed a powersports version of the battery since the aviation line was not yet available. The application was a two-stroke engine with a simple charging system not designed to charge any battery. This type of system produces a large AC ripple current that would typically be filtered by a very large lead-acid battery or a large capacitor. Lithium batteries require a good DC charge current. This thread is still available for reading, including replies from EarthX. Of note, in all four of these cases, the battery smoked and quit working, but it did not explode, catch fire, or start a fire. In each case, EarthX worked hard to understand how the situation came to be, and changed the manuals to better clarify when their batteries should not be used. The current edition of the manual, if followed, will prevent future versions all four of these scenarios.

—J.Y.

BMS features on its website, nor does it include any contact information to allow for further inquiry. Regardless of the brand of battery, some kind of overvoltage protection is crucial on the aircraft (if not within the battery itself), because the overvoltage condition is what will lead to thermal runaway (see sidebar).

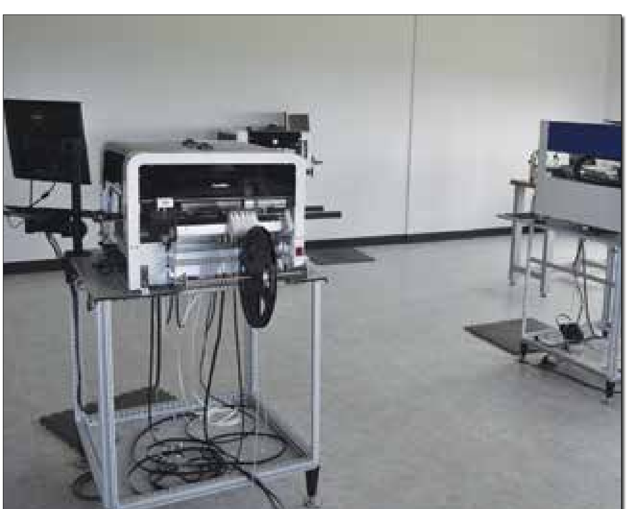
Another immediately obvious drawback to a lithium battery is in the initial purchase price. Apples to apples, the EarthX batteries are two to three times more expensive than a brand-name AGM sealed lead-acid (SLA) battery. Other brands of LPV lithium batteries are less expensive than the EarthX, especially those that do not support or endorse aircraft installations. In theory, a battery like the EarthX should be able to last longer than an AGM SLA, providing more value in the long run. Having said that, EarthX aircraft batteries have only been on the market for two years, so it is not yet proven how many operators will get such long battery life. Powersports users have had the batteries in service longer and are getting long-term durability, but our environment may not correlate exactly.

EarthX has grown into this facility, and by some measures, has already outgrown it. Three additional assembly tables are being created now.

A Visit to EarthX

With some background information out of the way, let's return to our tour of the EarthX factory. The innermost guts of an EarthX battery start out, like many things in our tangible world, in a factory in China. LFP cells are available for purchase from Chinese suppliers in various stages of assembly, from bare cells to complete batteries, branded to order, and ready to install in a vehicle. EarthX starts with a bare 4-cell pack, delivered from the single supplier that they have used for years. Reg has developed a relationship with this supplier, including half a dozen trips to their facility in China. Quality is his main concern, and as Reg says, "I'm not here to make the cheapest battery possible, or to import the cheapest battery from China." He could find comparable cells from the cheapest suppliers at 1/5th the cost of his current supplier, but those savings could easily be consumed by increased failure rates. Each cell in the pack is marked with a bar code, which specifies its manufacturing batch. The goal is to get a pack that has four cells that are as physically and chemically identical as possible, so that they will age and perform as identically as possible.

The pack has two large conductors, which are the positive and negative leads. There is a small balancing wire for each of the cells, and those leads are soldered to the BMS circuit board. This board is the heart of the EarthX battery and a big part of what makes it different. The board is designed by Reg and assembled on special machines right in



These are the machines that populate the circuit board with its tiny components.

Solder paste is applied to circuit boards in a method similar to silk screening.

These custom-made assembly and testing tables rotate to expose the battery candidates to a variety of tests and assembly processes.

their Colorado facility. It is a fascinating process to watch. A solder paste is applied to the bare circuit board with a technique similar to silk screening. Then the board is loaded into a machine not much bigger than a multifunction office printer. That machine grabs tiny surface-mount components off of reels and places them where they need to go on the board. The solder paste is just sticky enough to hold the components in place while the board is transferred to an oven. This is a very precise multi-stage oven that melts the solder paste, but to the casual observe it looks a little like the oven you might see at a fast food chain that sells toasted sandwiches. All of these steps could be completed overseas, but Reg designed the circuit to use surface-mount components, which allow for machine placement. The machine-placed components require so little labor that the cost advantage is not worth the supply chain and quality concerns of importing the boards. Reg says, "I could save 10% of the cost, but being able to say it's made in the USA is worth more than that to me."

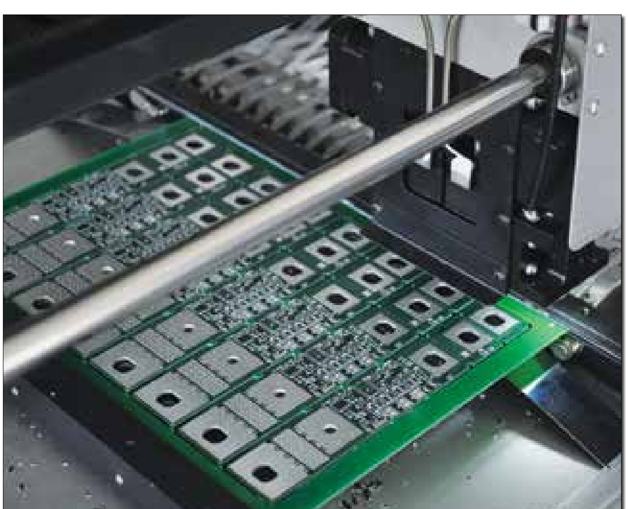
As of this writing, the hardware is on revision 7 for the powersports BMS, and revision C for the aircraft BMS. Software stored on the board is updated even more frequently. This software is the "secret sauce," since it contains the algorithms that have been honed over the years.

Testing and Final Assembly

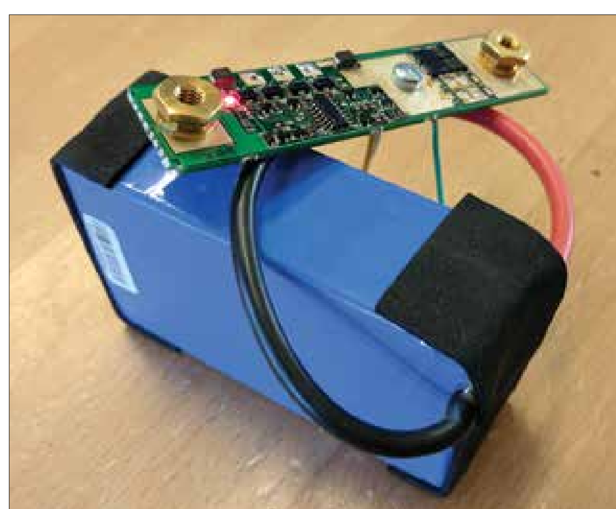
EarthX LFP packs will undergo several tests before they are delivered to a customer, and the first test begins in the three-month period it takes for them to get from their Chinese factory to the soldering table at EarthX. If there is a major flaw in the construction of the cell, it will show up as a variation in the voltage of the cell after this wait. Once the BMS is connected to the cell pack, tiny red LEDs illuminate on the circuit board. These LEDs indicate that the packs all have good cells that are matched within .001 volts of each other. If the pack fails this test, it is removed from the production line and recycled.

Next, the guts are placed into an injection-molded plastic case in the signature dark blue color. This assembly is installed on a big round table, specially designed by Reg to perform progressive tasks as the battery travels around its circumference. These tasks include discharge and charge tests, and if the batteries pass, the plastic cases are glued together in the final stages on the table. There are currently three tables in service, with more on the way. Each table is configured for one or two types of battery cases.

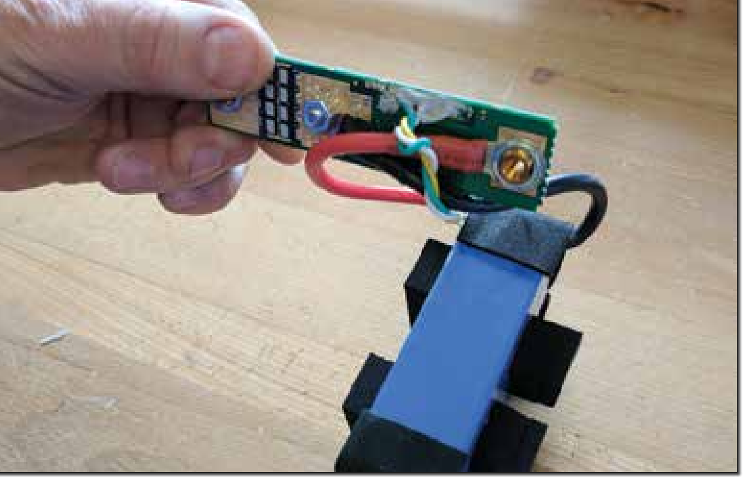
All of the cases are designed with the terminal lugs centrally located across the short dimension, which means that



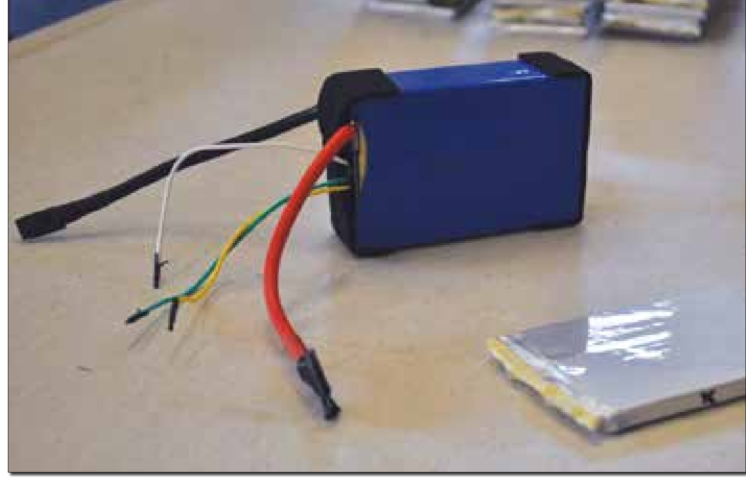
The components are placed on a batch of circuit boards before they go into the oven.



The battery management system tests for cell balance voltage within .001 volts and shows success with an LED indication.



Packs are padded with neoprene rubber, and the soldered balance wires are mechanically supported by a gray rubber-like compound. LPV batteries are generally more vibration-tolerant than lead acid batteries, but vehicles can be terrible operating environments.



This is what the battery packs look like upon arrival in Colorado. Four 4 Ah cells are stacked together and bundled in blue heat shrink wrap. Some batteries use a slightly larger 6 Ah cell.

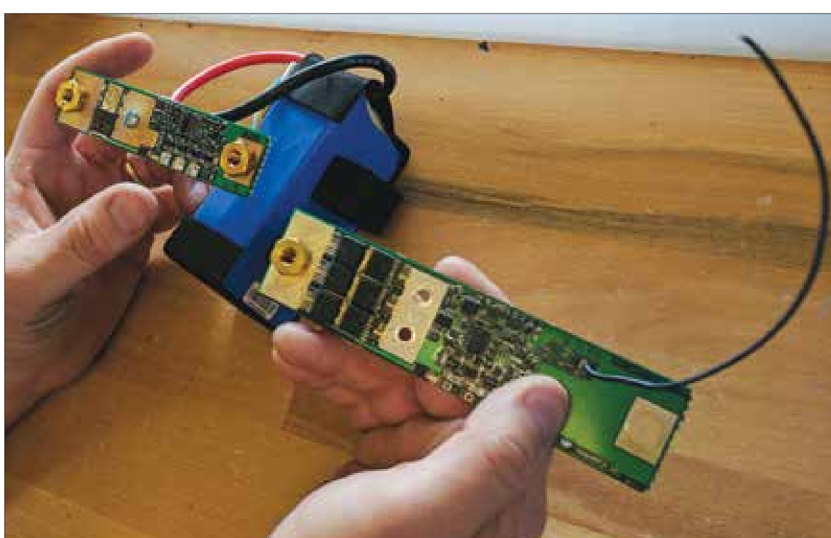
a single battery unit can be rotated during installation to serve the needs of the application, regardless of which side is positive and which side is negative. The aviation line includes four batteries, three of which are in the same size case. The exception is the ETX680C, which is specially designed to be smaller for space-critical installations. In the fall of 2017, a new aviation-specific model will be introduced that is vented for inside cabin installation. It will be called the ETX900-VNT. The case for the other ETX "hundred series" of batteries is similar to that of the Odyssey PC680, though there is enough variance that tight-fitting Odyssey battery boxes (like the standard Van's box) will be too small. Kathy gets frequent feedback from folks who would rather have the case of the EarthX be the same size as the Odyssey, but she says there is just no way to fit the lithium cells in the smaller space.

Made Specifically for Aviation

Some speculate that an aviation battery is just a powersports battery with a special label and a special price. For the EarthX line, this is not the case. The difference between the powersports BMS and the aviation BMS is visually obvious. The aviation system has dual redundancy of all management functions, so it is physically larger, and the circuit board is more populous. It also includes onboard circuitry that compares the two redundant systems to ensure that they are adequately matched and functioning correctly. Reg says, "Redundancy without the ability to isolate redundant components is not redundancy." Also immediately obvious is the small black wire leading out of the battery, which is the fault indicator. This can be connected to a stand-alone LED in the cockpit, or fed into an engine monitoring system to indicate on an EFIS/EMS display.

Why does the battery need its own indicator? The first rule of operating an airplane with a lithium battery is to not fly the airplane if the battery is defective. Reg says that users of lead-acid batteries can get away with operating on a marginal battery for a long time, by jumping the battery and carrying on until that doesn't work. Since a lead-acid battery will indicate impending failure by not cranking the engine, prohibiting flight on a bad battery is usually self-correcting, though there have been a few notable cases where jump starting an all-electric airplane has led to an engine failure after an anomaly that would have normally been manageable. Because the lithium packs have a higher voltage and energy delivery capability, a pack can still get the prop turning fast enough to start the engine, even if a cell is starting to go bad. This makes connection of the fault indicator absolutely mandatory, and Kathy points out that the indicator was not connected in any of the three known cases where their aircraft batteries have failed in service.

Does a lithium battery require special mounting considerations? In the E/A-B market, EarthX tries not to make recommendations about how and where the batteries should be installed, leaving that choice to the builder. Having said



The larger circuit board is for the aviation battery management system. Its protruding black wire is for the annunciator circuit.

The molded plastic case is designed with a tiny channel around its perimeter, which wicks the liquid glue after assembly.

Glue is used to permanently join the clam-shell halves. A small dot of residual glue leaves a shiny spot, which is sometimes mistaken for leakage.

that, the temperature tolerance of the lithium packs is better than with lead-acid batteries. No battery likes being in a hot place, but the EarthX batteries are designed to operate (including charges and discharges) with temperatures as high as 140° F, and can tolerate post shutdown engine compartment temperatures from -40 to 158° F. Lead-acid batteries are especially bad at handling high temperatures, in some cases experiencing shortened life span with exposure above 113° F. It is also worth noting that any concerns about the battery's environmental exposure are only concerns about its longevity, not about its safety. Thermal runaway for LPV cells is over 500° F, a temperature that is only obtainable with multiple failures of the charging system and BMS. Notably, the demands on the structural components of the battery box are much less because of the reduced weight.

Battery Selection

Choosing the right size of lithium battery starts with defining the mission of the battery. If engine starts are the only concern, then cranking amps will be important. If electrical architecture is based on getting a certain amount of run time after an alternator failure, then the battery also needs to be large enough to deliver that energy. Lithium batteries deliver their energy in a slightly different way than lead-acid batteries, which complicates the shopping process. In a lithium battery, the voltage stays higher throughout the discharge, until it nears the last 10% of capacity. From there, the voltage drops sharply. While the Odyssey PC680 is rated for 18 Ah (amp hours), we won't get that kind of use in an aviation setting because the voltage will become unusably low sooner in the discharge process. As Reg says, "If we are trying to run a light bulb, we'll get 18 Ah out of it," but a light bulb will glow at 4 volts, which doesn't do any good for powering an EFIS or electric ignition. Further complicating things, some of the lithium battery sellers have created their own terms to describe capacity. It is hard to make an apples-to-apples comparison of the rated Ah capacity between the two chemistries. He encourages customers to understand the capacity issue—and their energy needs—before deciding on a battery size, and EarthX is glad to help people understand this decision.

As consumers, we sometimes forget that the products we buy are created and sold by people. Having spent time with Kathy and Reg, just two of the staff at EarthX, it is clear that both are highly effective and multi-talented. It is doubtful that a small business could succeed if all of its team members were not. Reg developed the EarthX products and continues to engineer improvements. Kathy shines with customer service and sales skills, but also has the high level of technical knowledge required to support a line of technical products.

Looking forward, the company hopes to continue its recent double-digit growth. To date, over two dozen airframe and engine manufacturers are using EarthX batteries, demonstrating that the technology offers significant advantages and is becoming more accepted. In fact, Kathy says their fastest growing market segment is aviation. This is in part because there is less competition, and in part because the end consumer values a higher quality battery. She points out that generally, powersports customers are much more price sensitive than aviation customers. They hear that the battery costs $10 more and stop listening before they are convinced of the advantages of a sophisticated BMS and a battery that is made in the USA.

EarthX is also currently developing a certified version of their battery that will be available for aircraft customers requiring PMA parts. For folks running ancient flooded lead-acid batteries, the advantages of lithium will be spectacular.

Kathy says that EarthX will continue to expand its production capacity and improve its product line to make their batteries safer and better. She and Reg are the first to say that lithium batteries are not the ideal solution for all applications because the charging system and electrical design of the aircraft must be considered (see sidebar). But for builders who are willing to read the manual, and understand and provide for the needs of a lithium battery, there is real reward in weight savings, battery longevity and, hopefully, long-term value. ✢