Stan Honey's observation on LiFePO4 (aka LFP) batteries.

5 April 2020

There is lots of information available online.

- EV forums and websites
  - Evtv.me
- Cruisers Forums
  - Cruisersforum.com
- Technical papers
- Thesis on university websites
- Manufacturers websites
- Rod Collins has posted insightful summaries of his work on various forums and on his own site: https://marinehowto.com/ This site is a terrific source of information on lots of boat related topics. Search for anything posted by "Maine Sail" on any marine technical forum.
- There are useful articles at Nordkyn Design http://nordkyndesign.com/

- There are several vendors of well-engineered LFP battery systems; Mastervolt, Victron, and Lithionics are examples. I chose to assemble my own because the commercial batteries wouldn't fit the space I had. I was also intrigued by the project.

- Benefit. Calculation for Stan's LFP battery relative to the Gel Cell bank it replaces
  - Gel Cell bank to be replaced:
    - Two 180AH 6v gel cell deep cycle batteries in series. The overall specs were:
      - 10.875"H x 7.125"W x 20.5"L weight 136 pounds (for the two 6v batteries)
      - Of the 180AH capacity, less than 90AH were useful on a daily basis when running the engine to recharge due to the long (and frustrating) taper of charge acceptance.
      - $355 x 2 = $710 (West Marine)
      - Lifetime approximately 300 cycles or 10 years. Mileage of course varies based on depth of cycle and the amount of time that the battery spends at partial charge.

Original two 6v gellcells.

- LFP bank:
  - Eight CA180FI cells, wired in four groups of two parallel cells, with the four groups in series (2P4S). Each cell is nominally 3.4 volts, 180 AH. The overall specs are:
    - 10.93"H x 7.1"W x 22.36" L weight 100.5 pounds.
    - Of the 360AH capacity, about 270AH are useful on a daily basis due the high charge acceptance rate and very short taper of charge acceptance.
    - $229 x 8 = $1832 for the cells.
    - There are additional costs for the busbars, BMS, relay, alarm transducer, thermal cutouts, nema enclosure, waterproof switches, G10 plate, and waterproof cable glands. Probably another $300. I also upgraded the alternator and regulator but did not score those costs in the cost of the battery.
    - Lifetime approximately 2000 cycles according to the literature.

- Net, relative to the gellcells, the LFP bank is about the same size, weighs 75%, has 3x the useful capacity, has a 6x longer life, and costs 3x more.
  - The cost per useful AH is about the same. The lighter weight and smaller size (per AH) is a bonus.
  - The LFP battery is much cheaper than the gel cell if you calculate the cost per AH per cycle over the expected lifetime of the battery.
  - It saves still more if you take into account the fuel and engine wear saved by being able to charge much faster, but that is tough to quantify.

        - A commercial off-the-shelf LFP battery of this capacity, using similar LFP cells, costs about $7-10k. That is about 3x parts cost, which makes perfect sense as a markup on parts cost for a well-engineered and assembled product.

- Danger
    - The general wisdom is that LiFeP04 batteries, aka "LFP" don't burn. This is not entirely true; see the photo below. If fully-charged LFP cells are overheated they emit flammable gas. My impression from the literature is that this can be triggered by heating fully-charged cells to over 200 deg C. This can be caused by overcharging at a sufficient rate to heat a cell to over 200 deg C.
    - As an aside, LFP cells that are not fully charged are much more tolerant of heat.
    - It is rare for LFP cells to be triggered into burning by being crushed, mechanically damaged, or short circuited. This kind of mistreatment typically results in the venting of flammable gas.
    - Nigel Calder wrote a very good summary of the safety and danger of LFP batteries in edition 149 (June/July 2014) of the Professional Boatbuilder Magazine.
    - LFP cells have extremely low series resistance, and so extremely high short circuit current. So while it is a bad idea to accidentally short a lead acid battery with a wrench, it is an even worse idea to short a LFP cell.

See: http://www.batteryvehiclesociety.org.uk/forums/viewtopic.php?t=1825

- Overview of my LFP installation's safety provisions
    - Terminal fuse right at the battery. Whatever fuse is selected needs to have a high interrupt capability such as a terminal fuse or Class T fuse.
    - The busbars and terminals on the top of the cells are covered with a heavy vinyl cover to prevent accidental short circuits.
    - A BMS (Battery Management System) is used to monitor the voltage of every cell, and open the bank relay, disconnecting the battery bank, if the voltage on any cell drops below 2.8 volts or exceeds 3.65 volts. The low voltage cutoff protects the cells from over-discharge damage, and the high voltage cutoff protects the cells from overcharge due to a regulator or charger malfunction.
    - Thermal cut-offs (SDF DF077S), also known as thermal-fuses, are physically attached to every cell. They disconnect the bank by opening the battery cutoff relay if the temperature of any cell exceeds 77 degrees C. These cut-offs are entirely separate from the BMS. They are passive devices that are in series in the control wire to the Blue Sea 7712 (7713) auto-releasing magnetic-latch relay. If any of the thermal fuses opens that will disconnect the battery even if the BMS has failed. Thermal cut-offs are available in a wide variety of temperatures and cost only $1 each. The cut-offs that I selected have a cut-off temperature of 77C, and a holding temperature of 55C, which is 131F. I selected cut-offs with a sufficiently high holding temperature so that they will not nuisance-trip when the boat is stored out of the water, in the tropics. At the fractional C usage of LFP batteries on boats, combined with the low series resistance of LFP cells, there is nearly no self-heating. So a warm cell is an unambiguous sign of trouble. The 77 degree C cutoff temperature of these thermal cutoffs is far below the 200 degree C threshold where a fully charged LFP cell can go into thermal runaway.
    - Independent of the BMS, the Victron BMV700 battery sounds an alarm if the battery bank voltage gets higher than 13.9v or lower than 12.6v.
    - The alternator output is wired via a diode isolator (aka diode splitter) to the LFP bank relay and to the engine AGM battery. This protects the alternator, regulator, and onboard electronics if the LFP battery is ever disconnected while the alternator is charging because the alternator current always has an instantaneous place to go (i.e. the engine battery via the diode isolator). The BMS normally avoids an alternator load dump because it disconnects power from the alternator regulator prior to opening the LFP bank relay if there is an overvoltage disconnect. But if due to a BMS failure (or a human error) the LFP bank is ever disconnected when under charge, the diode isolator will prevent an alternator load dump voltage spike. There is more detail in the later paragraph on "Engine Battery Charging and Load Dump Protection".
    - The high-voltage-cutoff (HVC) relay that is driven from the BMS, and the "charge enable" toggle switch both disconnect the power input (Red, B+) from the regulator in order to disable charging. Note that the Balmar documentation for the MC-614 regulator states that the preferred method for the BMS to disable charging is for the BMS to disconnect the Brown ignition wire to the regulator. I chose to instead switch the B+ wire in part at Rod Collins' recommendation, and in part because if the battery is

getting overcharged as a result of a regulator malfunction, disconnecting the power to the regulator seemed more likely to remove power from the alternator field and so to stop charging.

Above see string of eight SDF DF077S 77 deg C thermal cut-offs in series.   These are the inexpensive ($1 each), passive, non-resettable thermal cut-offs often seen in hair-dryers, coffee-makers, electric heaters, and similar appliances with heating elements. The string is taped along the battery with one cut-off attached to each cell. The string is in series with the control wire to the main battery relay. If a thermal cutoff triggers, the battery is disconnected, independent of the BMS, or of any other electronics.

- CALB
  - CALB CA cells appear to be a good choice.
  - They apparently maintain balance well and have a long life.
  - Note for high latitude cruisers: LFP batteries must not be charged if they are below 0 deg C. Their discharge and storage range extends to -20 deg C.

- Pack design
  - My battery is configured 2P4S, or as four groups of two cells in parallel, with the four groups in series. I used eight CA180LI cells, yielding a 360AH battery.
  - Each group of two parallel cells is connected on its diagonals, into the series string, as is customary in battery design, in order for each cell in the bank to have the same busbar series resistance.
  - I chose to use braided busbars from evtv.me because they are slightly flexible and reduce the mechanical loads on the battery terminals.
  - McMaster carries M8 x 1.25 SS bolts that are 16, 18, 20, 22, 25 mm long which are handy to deal with the varying thickness of the busbars and terminals and still use most

of the threads in the battery poles which are made of soft aluminum or copper depending on the pole.

- I made 5/16 inch G10 end plates, and strapped the battery together with Kevlar straps. I chose Kevlar over SS banding to avoid conductive banding in the proximity of the battery. Some say that it isn't necessary to have strapped endplates in the low current application onboard boats, but CALB recommends the practice. Sally also had some left-over Kevlar strap from her sail loft so it was easy.
- CALB recommends to lightly sand the battery terminals. I sanded and then coated the terminals and busbars lightly with No-ox-id Special-A. Noalox is another, messier, alternative.
- Sally made a vinyl cover for the assembled battery to prevent accidental shorting of the cell busbar interconnects which have no fuse protection.
- The manufacturer CALB recommends that the cells be mounted terminals-up. Others have mounted cells with a narrow-side down with no apparent problems but mounting terminals-down or flat-side-down is ill-advised because it would disable the vents. My battery is mounted with the cells having a narrow side down. The cells are actually tipped up some because of the dead-rise in the hull.

Cell layout and busbar configuration. The small wires are for the BMS. They have 1 amp fuses in waterproof holders. The temperature cutouts are underneath the white insignia cloth visible between the two Kevlar straps. The terminal fuse is visible on the positive end of the bank.

- BMS
    - I used the Cleanpowerauto Housepower BMS and the 4S remote cellboard. Note that these BMS parts are no longer available. If I have to update the BMS I would similarly select one that does not need to have cellboards mounted on the battery.
    - I ordered a board with HVC set for 14.2 volts. The standard board comes with HVC set for 14.6. The website documentation isn't perfectly clear so one needs to specify. As you can conclude from the 14.2 HVC setting, I'm not planning to use the BMS for balancing, but instead am using it as a safety mechanism to disconnect the battery before a cell gets damaged due to too high or too low voltage (above 3.65v or below 2.8v).
    - I used the 4S remote cellboard instead of the individual cell boards so that the 4S cellboard could be mounted in a waterproof nema box adjacent to the battery, also containing the bms board, HVC relay, and alarm. All switches, cable glands, and other penetrations into the nema box are waterproof. LFP batteries are heavy enough so that they are sensibly mounted low in a boat, i.e. in the bilge. Things that are mounted in the bilge get wet and dirty. One drop of salt water or a small metal shaving on a cell board could ruin the surface mount circuit board, so I chose to not mount fragile bms boards on the cells themselves but instead mount them and all other delicate items inside the waterproof nema box. All parts mounted outside the sealed nema box are reasonably tolerant of moisture and dirt (e.g. relay, shunt, fuse, potted regulator).
    - The 14.2 HV and 11.6 LV bank voltage alarms from the BMS are unlikely to ever trigger because the Victron BMV700 that I use as an amp-hour meter is set up to sound the alarm if the bank voltage gets above 13.9v or below 12.6v. So the Victron will trigger a bank voltage alarm before the BMS on high or low battery bank voltage.

- Regulator
    - Nearly any sufficiently configurable smart regulator could be programmed to work. I use 13.8 volt bulk voltage, no temperature compensation, and a low float voltage.
    - I used a Balmar MC-614 which is very configurable. It will refresh your fond memories of 1970's era user interfaces. I set up the Balmar MC-614 with the following settings:
        - dLc 30 sec
        - AHL 13.9 volt
        - CL 13.9 volt
        - bv 13.8 Volt
        - b1c 0.2 (shortest possible)
        - Av 13.6 Volt
        - A1c 0.2 (shortest possible)
        - Fv 13.4 Volt
        - F1c 6 Hours (longest possible)
        - FbA 10
        - SLP 0.4 mVolt (minimum possible)
        - bEL b-9 belt manager

- There is a widely known trick with the Balmar regulators when lowering the set voltages: you have to reduce the float voltage first, then reduce the absorption, then the bulk.
- With this configuration, charging takes place in "bulk", the unnecessary "absorption" phase gets passed through quickly, and the regulator shuts off charging when it switches to the low 13.4v "float" phase. The battery is not being charged when in the "float" phase because 13.4 is very close to the open circuit voltage of 4 LFP cells in series (4*3.34=13.36v), but the alternator does carry any DC loads.
- I connect the power wire for the regulator via a relay controlled by the high-voltage-cutoff output of the BMS, so that the regulator is disabled if the BMS detects a bank voltage of 14.2 or higher, or a cell voltage of 3.65 or higher.
- I have a manual toggle switch also in series with the power to the regulator to make it easy to disable charging. LFP batteries are happiest stored at partial charge. As a result, there are times when I want to run the engine without going through a charge cycle that would fully charge the battery, e.g. motoring to a slip or boatyard before a period when the boat will not be used. There are other times that we sometimes disable charging such as low speed maneuvering in a marina, or when re-starting the engine when the battery is already nearly fully charged.
- Some folks state that a 13.8 volt (3.45v per cell) bulk charge will not fully charge a LFP battery. Whether it does or not depends on how low you let the charge current drop before terminating charging. A 13.8 volt charging voltage will overcharge and damage a LFP battery if you keep at it too long. With the MC-614 regulator settings that I use, the regulator switches from "bulk" at 13.8v when the charge current drops below about 25 amps. At that point the charge current is dropping quickly. I estimate that the battery is then charged to about 95% or more. In my case this conservative approach makes sense because I don't need the full 100% capacity of my bank and there are advantages to only charging to 95% state of charge. One advantage is the cells stay perfectly balanced. A second advantage is that the engine on a sailboat might be started several times per day when the battery is charged already. With b1C set to minimum time, and with a conservative "bulk" voltage of 13.8v, these "short cycles" do no harm. I sometimes use the manual switch to disable charging in these situations but it is a reasonable goal to have a charging system that doesn't depend on manual intervention.
- Pet Peeve on terminology: Balmar's terminology is unfortunate. For many years the "bulk" phase was when the charge source was putting out as much as it could and the voltage had not yet reached the "absorption" set voltage. The "absorption" phase was when the battery voltage was at the voltage set point and the charge current was decreasing. Finally "float" was when the smart regulator switched to a lower voltage. By adding a new mystery phase and labelling it "absorption" with yet another voltage set point, Balmar is just confusing things. But it does no harm. As mentioned, I just set A1c as short as possible so that the unnecessary Balmar "absorption" phase gets passed through quickly.

- Engine battery charging and Load Dump protection
    - I use a Mastervolt Batterymate 1602 FET-based zero-voltage-drop “diode battery isolator” (aka diode splitter). My engine battery is a Lifeline AGM, so the charge voltages for the LFP battery are compatible. The Balmar MC-612 regulator is located adjacent to the LFP battery with short and heavy ground and sense wires, so the LFP battery is at precisely 13.8v during acceptance charging (or the CV portion of “bulk” in Balmar’s odd terminology). The peak charge voltage is slightly higher (14.1v) for the Lifeline AGM engine battery due to the IR drop in the battery cables to the LFP battery but it ends up being perfect for the Lifeline AGM engine battery.
    - Diode Isolators are not as fashionable these days as are ACR’s (Automatic Charge Relays) but they have significant advantages. The major advantage of the diode isolator is that if the BMS (or a misguided human) ever disconnects the LFP battery when under charge, the alternator current always has some instantaneous place to go (i.e. to the engine battery via the diode isolator). Therefore there will never be an alternator load dump voltage spike that could damage onboard electronics or the alternator diodes. The regulator sense wire is connected to the output of the diode-isolator so if the BMS relay disconnects the LFP battery the regulator will continue to sense the charging voltage as the alternator continues to charge just the engine battery. Having the regulator sense wire on the output of the diode-isolator also allows the regulator to compensate for the voltage drop of the diode isolator. The use of a diode isolator results in more predictable behavior than an ACR, is simpler than an ACR, and does not rely on a mechanical relay. A diode isolator provides continuous protection against an alternator load dump which an ACR does not do. If the ACR relay happened to be open when the LFP bank disconnected, there would be a load dump transient that could damage the alternator and onboard electronics. FET based “diode” isolators have much lower voltage drop than diode isolators based on silicon diodes, so they don’t dissipate much heat.
    - There are a couple of other advantages of diode isolators.
        - When the engine is off, a diode isolator keeps the 12v from appearing on the back of the alternator, thus making servicing the engine safer and making a “service” disconnect switch for the alternator unnecessary.
        - If the alternator diodes were ever to fail shorted, the diode isolator would prevent the failed alternator diodes from shorting the battery to ground.

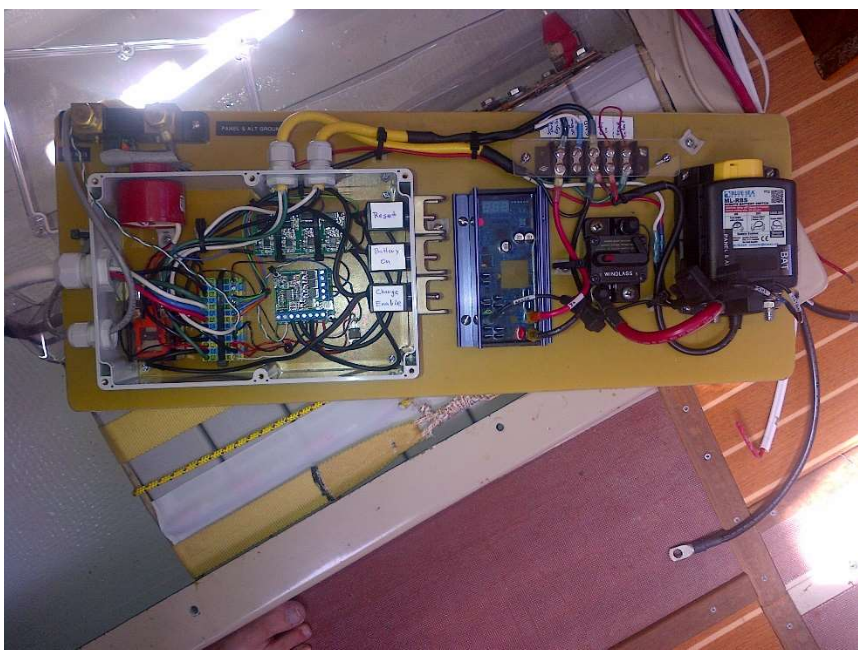
- Alternator
    - The high charge acceptance of a LFP battery can be tough on alternators. Normal alternatives are to use a large-frame high-temperature rated alternator, use an alternator temperature sensor with a regulator that limits field current accordingly, or just limit alternator field current and run the alternator well below its maximum capability.
    - Many have observed that that small-frame alternators overheat if run continuously at full output. I selected a Balmar AT-165 which has a significantly higher rated output

than I need. It is small-frame, fits easily on a Yanmar, and uses the Denso hairpin stator which is said to be more efficient than a conventional winding. I run it at Balmar's belt manager setting of b-9, which is 55% of full-field. This setting limits the max alternator current to about 110A which is close to 0.3C for my battery, which is the CALB recommendation for charge current. The AT-165 is able to put out 110A continuously without exceeding 220 deg F, even in the small Cal 40 engine space.
    - I installed the Balmar serpentine belt kit. This was supposed to be a "plug-and-play" installation on my Yanmar 3GM30FV, but wasn't. I had to buy shorter belts (390J10), machine the crankshaft sheave spacer to be 0.12 inch thinner, and put washers in the saddle mount of the alternator to move it away from the engine 0.10 inch. After those adjustments it worked perfectly and it's terrific to have no belt dust. McMaster carries many sizes of serpentine belts.

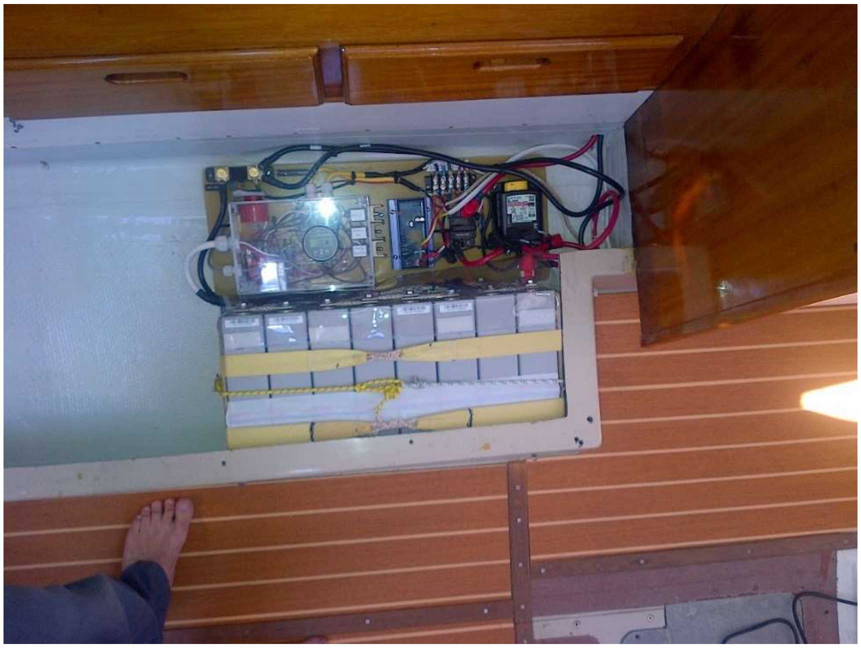
- Shore charger (i.e. shore power supply)
    - When you are in a slip, plugged into shore power, you have to deal with LFP batteries entirely differently than lead-acid batteries of any type (liquid, gel, or agm). Lead-acid batteries of any type benefit from being float charged at 100% because it avoids sulfation. LFP batteries are best stored at 50% charge or lower, and suffer if kept at 100%. This difference requires a significant change of attitude. With lead batteries on float charge, the boat is always "ready-to-go" with fully charged batteries. With LFP batteries that are around 50% charge, you have to either charge them before departure, take advantage of them getting further charged by the engine as part of powering out of the slip and hoisting sails, or be happy to leave the slip with batteries that are not fully charged. It is worth noting, however, that our LFP battery has 3X the useful capacity of our previous lead acid battery, that was the same physical size. So even if we leave the slip with the LFP battery half charged, we have 1.5X more usable stored energy aboard than we did leaving the slip with a fully charged lead acid battery.
    - I use a high-quality, regulated, remote-sensing, low-ripple, DC power supply (Kepco RTW 15-20KC). I can use it to charge the battery if there is a need. Normally when the boat is in a marina/slip with shore power available and we are onboard, I leave the LFP battery disconnected at about 50% state of charge, and use the DC power supply to power the boat's electrical system directly, with no battery in parallel.
    - If DC power supplies are to be capable of charging batteries, they need to have "rectangular current limiting", or "constant current limiting" which are obscure ways to say that the power supply needs to be able to run continuously at its current limit when it can't reach its voltage set point. The Kepco RTW 15-20KC has this property and has a wide input range of 85-265 VAC, 47-440 Hz, which is helpful if the boat ends up overseas, at the end of a long dock with low voltage, subject to boatyard AC transients, or if I ever have to get AC power from a cheap, unregulated, portable generator.
    - The Kepco power supply is electrically quiet (+- 0.05v output ripple, FCC Class B) and has terminals for remote voltage sense. These are advantages offered by only the best marine battery chargers. Kepco power supplies also have the characteristic that all well

designed DC power supplies have, that it is fine to have their output hooked to a battery when their AC input is unpowered.

- Battery and charge monitoring
  - LFP batteries have an extremely flat charge/voltage curve, so the measurement of bank voltage cannot be used to determine the state of charge the way it can with a lead-acid battery.
  - I use a Victron BMV700 as an amp-hour meter to track state of charge, but there are lots of options.
  - I set up the Victron to sound an alarm of the battery voltage exceeds 13.9 or drops below 12.6. (This is independent from, and will sound earlier than, the BMS bank voltage alarms at 14.2 and 11.6)
  - LFP batteries are extremely efficient so I set the charge efficiency factor to 100% and the Peukert exponent to 1.0. These settings cause the Victron amp-hour meter to estimate that the battery is fully charged just slightly before the end of each full charge cycle. This causes the Victron amp-hour meter to reset to 0 (i.e. full) with each full charge, and so stay synchronized.



Above, G10 board that holds associated battery electronics: the BMS, HVC relay, and alarm are in the Bud box. The Balmar regulator, windlass circuit breaker, and Blue Sea 7712 (now 7713) auto-releasing relay controlled by the BMS are more tolerant of moisture and so are mounted outside the Bud Box on the G10 plate. The Victron BMV700 is in the lid of the Bud box, which isn't in place in the above photo. The three switches on the Bud Box are: bms reset (momentary), battery/bms on, and charge enable. The Bud box and all cable penetrations, switches, and the alarm mounted through the box are all rated for being waterproof.



Final installation under starboard settee in Illusion, same location as previous two 6v gel cells. The lid of the nema waterproof Bud box is in place with Victron display visible. The heavy vinyl cover for terminal and busbars is in place, but barely visible.

Parasitic Power Drain measurements:

- 4.5 ma for the 4s cellboards.
- 12.8 ma with battery off (includes cellboards, Victron battery monitor, and BS7712(7713) relay
- 20.8 ma with battery on (includes cellboards, Victron battery monitor, BS7712(7713) relay, and bms).
- Background on parasitic power: I used a Blue Sea 7712 (now 7713) auto-releasing magnetic-latch relay instead of the Tyco or Blue Sea 9012 solenoid which is typically used. The solenoid has 130 ma holding current which would have been annoying for a boat as simple as a Cal 40. The Blue Sea 7712(7713) latching relay has a continuous current drain of <13ma. The HousePower BMS has an "open-drain" MOSFET pull down output for the normal solenoid control, so I used a P-Channel MOSFET (STP10P6F6) and a 100k resistor to interface to the control wire for the 7712 (7713) relay which needs a +12v pull-up logic input. The P-FET is just visible in the lower right corner of the Bud Box. I chose a TO-220 packaged P-FET not because I

needed the dissipation, but only because it was easy to mount the tab with a nylon screw and directly solder wires to the pins, “dead-bug” style. The wiring of the P-FET is visible on the schematic sketch. As usual the gate of the P-FET is attached to the “E” open-drain output of the BMS, the source of the P-FET is connected to the Relay+ connection on the BMS, and a 100k resistor is connected between the source and the gate of the P-FET to pull the gate up. The drain of the P-FET is connected to the red control input wire of the Blue Sea 7712 (7713) relay, in series with the thermal cut-offs. The P-FET uses no current beyond the 0.13 ma of the 100k pullup resistor. When controlling the Blue Sea 7712 (7713) there is no need for a “free-wheeling” or “flyback” diode because the control input to the 7712 (7713) is actually a logic input to a microcontroller within the 7712 (7713), and is not a relay coil, so there is no inductance.

- Note that the Blue Sea 7712 (7713) is an auto-releasing remote switch, it is not “bi-stable” and is not controlled by pulses. When its control input is at +12, the switch is on. When the control input is disconnected or at 0v, then the switch is off. It automatically turns off when its control input goes to 0v.
- When we leave the boat in storage for months, we discharge the battery to 50% and then disconnect the battery entirely, to eliminate all parasitic drain from the cellboards, Victron monitor, and BS7712(7713) relay. We do this by disconnecting the positive battery cable and removing the 1A fuses to the cells.

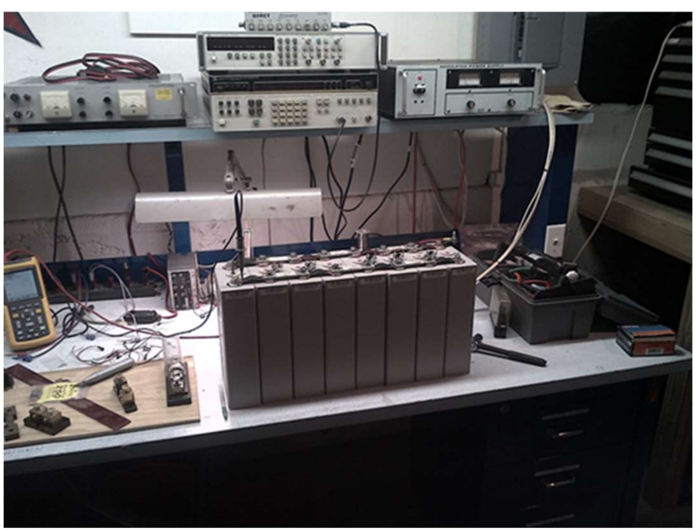
Settee back in place.

- Thoughts on Balancing
  - I “top-balanced” the cells when I received them. I temporary used the busbars to connect all cells in parallel, creating a 1440 amp hour, 3.4 volt battery, then charged it to 3.600 volt with a laboratory power supply, connected to diagonal corners of the battery as is usual practice so that every cell has the same series connection resistance. The laboratory power supply had remote voltage sense wires, which is a big help and can be used to keep the battery terminals at exactly 3.600 volts independent of the charge current. Initial charging to 3.600v took a couple of days using the 50 amp, current limited, laboratory power supply.

I let the parallel cells sit until little current was flowing between cells via the busbars. I then separated the cells and re-bussed them into their 2 parallel, 4 series configuration, and discharged them to 50% for storage prior to installation.

  - High quality laboratory power supplies are ok to have their output connected to a battery even when their AC input is disconnected or when they are shut off. This characteristic is essential for this use of a lab power supply.

- If a cell balance problem does emerge, the BMS system will cut out either for a low cell voltage on discharge, or a high cell voltage on charge, before any damage is done. I also check cell voltages occasionally with a 1 mV resolution DVM when the battery is fully charged. One can't, of course, detect a balance problem at mid-charge because LFP cells have such a flat voltage/charge curve. Whenever I've checked after a full charge, the cells have all been within a few millivolts, so no evidence of any drift in balance has emerged so far.
- If I did have a balance problem, there are three options to fix it:
  1. I could fix it by re-bussing the cells in parallel again and charging to 3.600 volts. This would only be a dockside exercise.
  2. I carry onboard a 0.5 ohm 50W resistor with some clip leads. I could do a rough rebalancing after a full charge, by discharging the highest voltage cell(s) one at a time to get closer to the other cells. This could be done at sea. I have not tried this as the cells have stayed in perfect balance so far.
  3. In principle another approach would be to disable the HVC on the BMS, disable the HV alarm on the Victron, and then charge at 1 amp or less for an extended period letting the bank voltage rise to 14.2v. This would let the limited shunt capability (1 amp) of the cellboards slowly fix the imbalance. This is not an attractive option because the 1 amp shunt current capability of the cellboards would require holding the battery at a voltage of 14.2v for an extended period, which is tough on the battery.
- I haven’t had a balance problem but if I did I would use option 2 above to address it.



Eight CALB CA180FI cells, during initial balancing with all cells in parallel. 50A, current limited, remote sensing, lab power supply is on the right side of the upper shelf.

Voltage Table   Note that the bank voltage column is of course 4x the cell voltage column; I show both for convenience. The values in parenthesis are included as a convenience but the voltage in the column without parenthesis is the significant value in each row. Winston and some other LFP cells may have different voltages. This table contains my impressions of the appropriate voltages for CALB CA cells.

Cell voltage	**Bank voltage**	**notes**
3.65		Cell level protection, BMS open circuits battery
(3.55)	14.20	BMS bank HV alarm
3.55		BMS cell shunting starts
	13.9	Stan's battery monitor HV alarm.
(3.45)	13.8	CV charging. Stan's Balmar Bulk Voltage.
(3.4)	13.6	Stan's Balmar Absorption Voltage. The Balmar regulator passes through this stage very quickly because when the Balmar switches to Absorption the current drops dramatically.
(3.35)	13.4	Stan's Balmar Float Voltage. This stops charging but does allow the charging system to carry loads.
3.34	13.36	Resting open circuit voltage with battery fully charged. Approximate.
3.15	12.6	Resting open circuit voltage with battery 80% discharged. Approximate.
	12.6	Stan's battery monitor LV alarm
3.00	(12.0)	CALB spec, stop discharge
(2.9)	11.6	BMS bank LV alarm
2.8		Cell level protection, BMS open circuits battery
2.5		CALB spec: irreparable cell damage begins at this voltage.

Summary Observations after Three years of off and on cruising

- One characteristic of the LFP battery that is surprisingly liberating, is the fact that the battery is happiest stored at partial charge. This frees us from the tyranny of always trying to fully charge a lead-acid battery to avoid sulfation. We only fully charge the battery if the engine is running anyway, and we are intending to continue to use the boat.
- Another characteristic of the LFP battery that is immediately noticeable is the benefit of the high charge acceptance. Over 20 months of cruising over four seasons, from San Francisco to Rhode Island via the Panama Canal, we only ran the engine just to charge three times. Whenever we happened to run the engine anyway to get on and off the hook, that engine usage charged the battery sufficiently to last us for several days. If the battery is fully charged, it can supply us for 5 days at anchor or 3 days underway, including refrigeration.

- We have no additional charge sources such as wind or solar. Given our experience so far we see no need to add additional charge sources and their associated clutter on deck. Our occasional use of the engine for propulsion keeps up with our energy use, given the high charge acceptance rate of he battery, and the large capacity.
- Living on shore-power in a slip is different. When we arrive at a slip we run the boat off the LFP battery until the battery is discharged to 50%. We then disconnect the battery and run the boat directly from the DC power supply connected to shore-power. It still feels a bit odd to pull into a slip and not connect to shore power.
- The cells have stayed in perfect balance so far.