

# OE101: Quantifying Battery Capacity for Marine Applications

*By: Kevin Hardy, Global Ocean Design,  
Ron Lugo, Battery Concepts*

## Introduction

Batteries permit the untethered operation of instrumentation and vehicles. Duration is a matter of capacity and discharge rate. Several factors will affect the deliverable energy of a battery, which may result in less than the catalog rated capacity, such as a high discharge rate. This primer will discuss multiple means to determine the actual energy available, using the more common chemistries applied to oceanographic research as examples. This is a large subject to cover in a few pages, and readers are urged to follow their curiosity into this hugely fascinating field.

## Battery basics

A cell generates electrical power through the application of the different electrode potentials of two galvanically active materials in a conducting electrolyte. The galvanic difference between the cell anode and cathode is called the potential and measured in volts. A battery is made from a number of cells in a series. The capacity of a battery is its ability to discharge current for a period of time, measured in amp-hours. A battery's energy, measured in watt-hours, is its capacity times its average potential. A battery pack is the assembly of batteries either in a series, to increase voltage, in parallel, to increase current capacity, or both.

There are two broad classes of batteries, primary and secondary. Primary cells can be used once, as the chemical process that produces the current is irreversible. Examples include alkaline and lithium cells. Secondary cells can be recharged by application of reverse current from a charger. The interior anode and cathode plates are rebuilt in the process. The regeneration process is not perfect, and some material is lost in each discharge-recharge cycle. This limits the number of times the battery may be recharged, known as cycle life.

## Factors Effecting Capacity

Batteries are based on chemistry. The chemical reaction rates of liquids and solids are largely driven by temperature. The vast majority of reactions depend on thermal activation, so the fraction of the molecules that possess enough kinetic energy to react at a given temperature will determine the capacity of the cell. The colder temperatures of the deep sea will lower the

capacity of most stored energy systems. Changing the pressure on a reaction that involves only solids or liquids has no effect on the rate.

Batteries are assigned a capacity rating based on a moderate Discharge Rate. If the actual rate exceeds that moderate discharge rate, the battery will be depleted faster, and not provide the assigned rated capacity. Operating a battery at its maximum current rating, say a 5Ah battery at 5A for 1 hour, would be destructive to the battery.

Many batteries have a self-discharge rate, which means that even on the shelf under no load, the cell's reactants will slowly combine and reduce the amount of energy available. Rechargeable batteries may be put on trickle chargers to prevent this, as on a cabled-to-shore node, but untethered vehicle designers have to consider this.

Some battery chemistries, principally Nickel-Cadmium (NiCd) and Nickel Metal Hydride (NiMH), have recharge memory effects. The condition describes the way these batteries gradually lose their maximum energy capacity if they are repeatedly recharged after being only partially discharged. The battery appears to "remember" the smaller capacity.

Physical Modifications to a battery, including means to pressure compensate the cells, may affect battery capacity.







*Figure 1: Launching the Woods Hole Oceanographic Institution's SeaBED AUV draws a crowd of interested penguins. Several factors, including temperature and discharge rate, can affect battery capacity. Courtesy H Singh, Northeastern University (c) Woods Hole Oceanographic Institution*

### Common Batteries in Marine Applications

Certain chemistries have found wide use in the marine field for their availability, energy density, ease of handling, or cost. These include primary cells such as alkaline and lithium, and secondary cells including Nickel Metal Hydride, Nickel-Cadmium, Lead-acid, and recently lithium ion and lithium polymer. Each have advantages and disadvantages, and choosing one generally involves some measure of trade-off.

**Alkaline (alkaline-manganese dioxide):** These primary cells are available in the widest number of standard sizes, and are commonly available around the world. This is handy if you are in a remote port and need to cobble together a spare battery pack. Numerous domestic manufacturers can assemble the cells into battery packs for you. Spot welding stainless steel tabs to the ends of the cells provides a ready way to join the cells into battery packs, and provides for a solder tab to attach a wire and connector. Because of the sealed metal cylinders, these cannot be pressure compensated. As the temperature drops to 0°C, these cells lose on the order of 1/3 of their capacity. As current drain increases, the temperature impact becomes more dramatic (ref: Duracell). Tip: Don't rely on spring-loaded battery holders for critical applications. Spot welding or soldering is a sure thing.



**Lithium-iron (Li/Fe):** These primary cells work as a replacement for alkaline batteries with a 1.5 V nominal voltage. Energizer Ultimate Lithium brand AA, AAA cells and 9v batteries employ this chemistry. These have 2.5 times higher capacity during high current discharge cycles than alkaline batteries, better storage life due to lower self-discharge, and more capacity at lower temperatures. The temperature effects on capacity only begin to show degradation after the cells pass below 0°C. (ref: Energizer)

**Lithium (Lithium-thionyl chloride, Li-SOCl<sub>2</sub>):** These primary cells have the highest energy density of all common cells, and the ability to deliver large amounts of current in a very short period of time. As a consequence of earlier misfortune, each cell is built with an internal fuse to protect it from being shorted and discharging rapidly with its attendant problems of outgassing and possible explosion. The metallic lithium, contained inside a thin stainless steel cylinder, is also extremely reactive with water. If the pressure case holding the cells leaks at depth, the cell will crush, and lithium metal will be exposed to seawater. The subsequent violent reaction will likely blow the endcaps off the pressure case at depth, even if a Pressure Relief Valve (PRV) is employed. If the housing is on a mooring, it may be

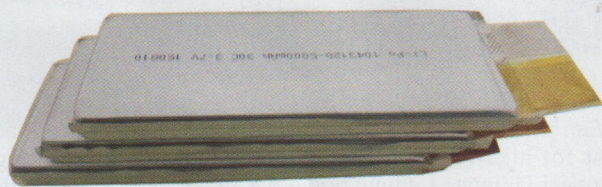


recoverable. By the time it gets on deck the reactive lithium will have been fully consumed and no longer pose any danger, though the smell of sulphur will be obvious.

**Nickel Metal Hydride (NiMH):** are replacing NiCd's in many applications. They self-discharge in 2-3 months, and do display some memory effects. They can suffer longevity issues with deep discharge. NiMH are themselves being superseded by Li-ion and LiPO batteries.

**Lithium-ion.** These secondary cells are not subject to memory effect, capable of moderately deep discharge, and much safer than primary lithium cells. They do require built-in protection against both excessive discharging and overcharging. Special charging stations isolate and charge individual cells to provide a balanced charge on all cells in the battery. They have a relatively low self-discharge rate, about 6% per month. They are used in applications requiring lightweight and high power drains such as drones and power tools. Li-Ion batteries use a flammable solvent-based organic liquid as the electrolyte. This electrolyte is responsible for the lithium ion exchange between the anode and cathode plates. Li-Ion batteries are usually encased in a hard metal can to keep the electrodes wound tightly against the separator sheet, adding some weight and limiting the number of shapes and sizes.

**Lithium Polymer (LiPO)** a lower cost version of the Lithium-ion battery. It cannot deliver the high current bursts of the Li-Ion. A LiPO battery doesn't use a liquid electrolyte as does the Li-Ion, but a dry, thin electrolyte polymer separator sheet that allows for the lithium ion exchange, hence the name "Lithium Polymer". This separator is laminated between the anode and cathode plates in a construction sometimes called a "jellyroll". This method allows for a very thin and wide range of shapes and sizes of cells. Li-ion batteries are considered safe for the trashcan and landfills once fully discharged, which manufacturers suggest may be done by dropping the old pack into a bucket of saltwater. There is lots of information available on the web from manufacturers, plus serious amateurs and RC clubs, such as RCHelicopterFun.com.



**Figure 2:** LiPO pouch cells have been shown to operate in ambient pressures to 20,000psi. Their solid-state protective circuitry must likewise be pressure tolerant.

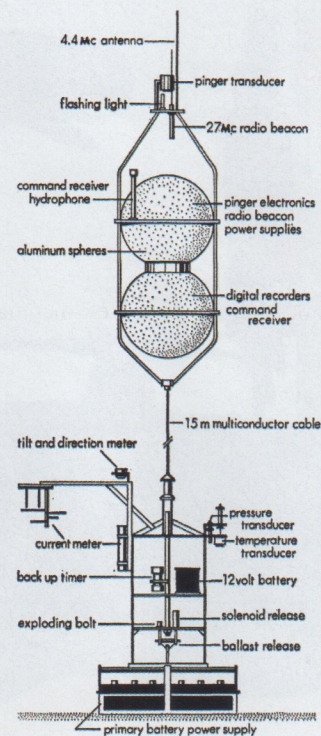
Of special interest for marine applications, LiPO batteries are offered in a "pouch" design, with a soft, flat body. The absence of a hard case gives pouch cells the highest energy density of any battery available. They still require some means of general structural support. The pouch is vacuum-sealed, with all voids filled by a gelled electrolyte. Thus, there are no implodable spaces. Pouch LiPOs have tolerated 20,000 psi immersed in mineral oil inside a Ziplock™ bag, and shown no degradation. The advantage to designers is two-fold: 1) battery packs carried on the outside of a pressure housing only subtract their water weight from the overall buoyancy, while carried inside, they subtract their air weight; and 2) it is easier to exchange batteries on a small vehicle by unplugging the used battery packs and plugging in the replacement charged ones. This benefit comes at the expense of additional underwater connectors.

**Lead-Acid:** The venerable lead-acid battery comes in three variants: 1) wet-cell or flooded, 2) Absorbent Glass Mat (AGM), and 3) gel electrolyte cells, the latter two considered valve regulated lead acid (VRLA), maintenance free designs. Lead-acids are temperature dependent, and their capacity may fall to as low as 60% of rated capacity as they approach 0°C depending on current drain.

Lead-acid wet-cells must remain upright or the electrolyte, a 35% sulphuric acid and 65% water solution, will spill. They can be exposed to high ambient pressure, and maybe mounted outside the hull. If exposed to seawater, they must be pressure-compensated. Any compensation fluid must consider specific gravity, miscibility, and surface tension with respect to the electrolyte.

If sealed with a rubber diaphragm, the battery must be vented to eliminate gases formed during charging. (Myers, 1968) An innovative alternative to pressure compensation was invented by Frank Snodgrass, Scripps Institution of Oceanography, in 1968. His wet-cell automotive batteries were open to the sea at the top, filed to the cat eye fill indicator with electrolyte. A PVC riser tube was placed over each cell and filled with an immiscible partition fluid heavier than seawater ( $\text{sg}=1.025$ ) and lighter than the battery electrolyte ( $\text{sg} 1.265$ ). The original cell vent cap was screwed into the top of the riser pipe to vent the gases associated with charging. Wires were soldered to the lead posts. The lead-acid battery was intended as an expendable ballast weight. Hence, the modified battery assembly was contained in a low-cost plywood box potted with hot tar. A pressure-compensated pull-apart connector allowed the simple disconnect of the electrical leads as the vehicle released its ballast frame. (See Figure 3).

Absorbed Glass Mat (AGM) lead-acid batteries are constructed differently than the wet-cell battery. AGMs are considered a "Recombinant Gas Absorbed Electrolyte" battery. Loss of charge due to self-discharge is 3 to 10 times better than gel cell sealed lead-acid, and 5 to 50 times better than wet-cell lead-acid batteries. In AGM batteries, also called starved electrolyte batteries, there is a thin, ultra-fine fiberglass mat sandwiched between the plates of each cell that is saturated with battery acid to about 95% of what it can hold. This glass mat absorbs and immobilizes the acid while still keeping the acid available to the plates. The mat is slightly compressed between the plates when assembled in a frame. Because the plates and mats are packed fairly tight, they are virtually immune to vibration. The remain-



**Figure 3.** The Munk-Snodgrass deep sea instrument capsule with expendable ballast frame and lead-acid batteries, 1968 (*Science*, Vol 162, #3849, Oct 4, 1968).



ing volume around the plates is air-filled, so that even if the battery is broken, no electrolyte will be spilled. It also makes the AGM battery lighter. Since the glass mat restrains the electrolyte, the AGM may be used in any orientation. Should an AGM battery be adapted to a pressure-compensated battery system, however, great thought must be given to the introduction of a fluid other than electrolyte into the interior of the cells. Should the compensating fluid with its dielectric properties wick into the glass mat, at worst displacing the electrolyte, a reduction in capacity will follow as areas of the plates become isolated or contaminated. A capacity test would be wise to validate the design and resultant performance.

Gel cell Sealed Lead-Acid (SLA) batteries substitute a gel-type electrolyte for the liquid in basically a wet-cell lead acid battery. This permits it to be used in any position. They are operated at a lower potential to prevent gas generation, meaning they are never fully charged, resulting in the lowest energy density of all secondary batteries. They have low self-discharge rates, and no memory effects. They cannot be fast charged. Gel cells are still being sold, but getting harder to find as the AGMs are surpassing them in performance.

### Quantifying Battery Capacity

There two means of determining battery capacity, one by estimate, and the other by measurement. The first method relies on the use of battery cell manufacturer spec sheets, an understanding of the environment the batteries will be used in, and the expected battery performance characteristics. Data sheets are available on-line from all manufacturers, such as Duracell, Energizer, and Panasonic.



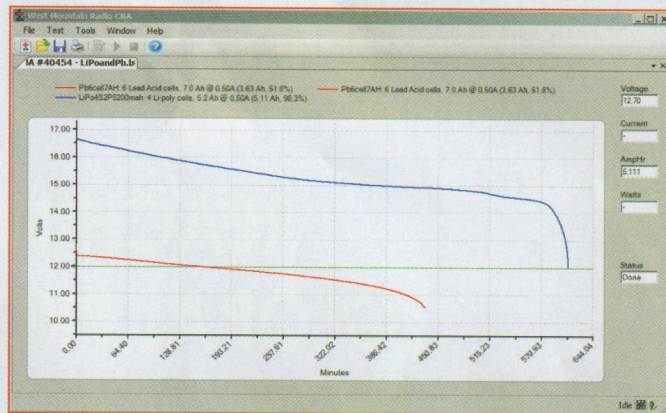
**Figure 4:** The rugged West Mountain Radio Computerized Battery Analyzer (CBA IV) attaches to a laptop by a USB cable, and to a battery by Powerpole® Connectors.

The second means is to measure the battery performance directly. This is best done by use of a computer controlled battery analyzer, such as the Computerized Battery Analyzer (CBA IV), from West Mountain Radio. Originally intended for ham operators running sets in the wild on Field Day, the CBA IV can test virtually any type or size of battery, any chemistry or number of cells, up to 55 volts. The CBA IV is capable of tests up to 100 watts continuous, or 150 watts for short periods of time. With an optional amplifier, tests can be done to 500 watts. Additionally, up to four amplifiers can be used at once for a total test power of 2000 watts. The basic model is about \$160, while the commercial Pro version is just \$40 more.

The CBA tests the total amount of energy stored in a battery (capacity in amp-hours), graphically displays and charts the voltage versus time using a constant current load. Graphs may be dis-

played, saved and printed. The axis parameters can be changed at anytime. Multiple test graphs of the same battery, or multiple batteries, may be compared or overlaid. The battery test data can be printed on any printer. Test result labels can be printed to put directly on the tested batteries. An optional external temperature probe provides automatic over-temperature test cutoff.

The intuitive software supplied with the CBA is designed to protect both the CBA and the batteries being tested, providing automatic sensing of the battery cell count, a safety check of the test rate, and recommending a minimum safe discharge voltage. Capacity discharge tests may be viewed in Amp Hours or Watt Hours. A lab calibrate current adjustment improves the accuracy for testing at very low discharge rates, or for critical applications. The Charge Monitor Test charts and records the voltage rise during recharging, so you can see the performance of the battery under those conditions.



**Figure 5:** LiPo & Lead-acid battery testing showing minutes of use at 500ma average current. (Courtesy West Mountain Radio).

Primary cells may be tested and used to predict performance of a larger battery pack. Once discharged, however, they are done, so be wise about the number you batch test.

Secondary cells or batteries may be tested then recharged. The CBA IV is also capable of a Power Profile test, useful for power supply testing or solar cell analysis. The resulting graph displays Voltage vs. Amps or Watts. This will be useful for designers working with solar recharging systems on buoys and unmanned surface vehicles (USV).

### Conclusion

Battery testing may be done for manufacturer quality assurance or end-user battery characterization before specifying a battery for critical use. Testing to qualify a particular battery system for a project must replicate the expected conditions of use. Battery technology is a field that continues to improve. Many technical books and reference guidelines have been published on the subject. Certain chemistries, like mercury and cadmium, are disappearing due to environmental hazards, while others, such as rechargeable Lithium polymers, are showing great promise for increased stability, energy density and low cost. Transportation issues for some battery chemistries may also affect the choice of the ideal battery.

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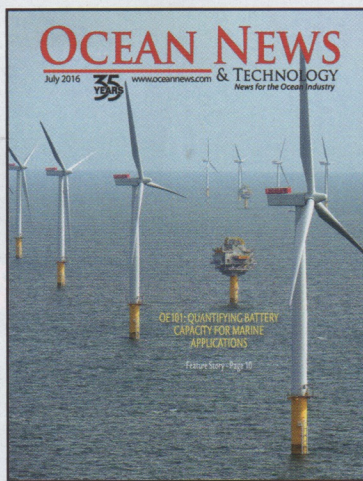
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