Application Note:
AGM vs LPF Battery Testing

Michael Fox, N6MEF

Revised: 08-Feb-2019

Table of Contents

Introduction

This application note summarizes the comparison of an Absorbed Gas Mat (AGM) Lead Acid battery to a Lithium Iron Phosphate ($LiFePO_4$ or LFP) battery. The recommended battery size from the Santa Clara County ARES/RACES Go Kit list was used as a baseline for the performance tests. For AGM-type batteries, this is 12 Volts, 26 Amp*hours (Ah). The common claim is that a lower Ah LFP battery can replace a higher Ah AGM battery. Therefore, this application note compares the test results for a 26 Ah AGM battery with the results of the same tests run on a 20 Ah LFP battery.

Several types of tests were run, representing several different use cases. Of course, real-world usage will likely be different for each person. But the data provided herein should be enough to interpolate/extrapolate the expected run times for other use cases.

Test Environment

Batteries Under Test

AGM Battery

The device under test is a PowerSonic PS-12260, 12V 26Ah Absorbed Gas Mat (AGM) battery. The battery is approximately two years old. It has only been used two or three times and was fully charged after each use before storing. The last time it was used was approximately a year ago. Prior to running these tests, the battery was discharged and charged a few times. As seen in the constant current discharge test results, the battery outperforms the expected values from the datasheet. So, it is assumed to be in new or near new quality.

LFP Battery

The device under test is a Bioenno BLF-1220A, 12V 20Ah $LiFePO_4$ (LFP) battery. The battery is brand new. It was charged and discharged a few times prior to running these tests.

Test Device

The test device used was a West Mountain Radio Computerized Battery Analyzer IV Pro (CBA IV Pro) plus one CBA Amplifier, which is required in order to draw more than 100 Watts. For the standard discharge test, the standard software license can be used. To measure more complicated duty cycles, such as X Amps for some time for transmit, then Y Amps for some time for receive, then repeat, the “Multiple Discharge” test was used, which requires the extended software license.

Test Parameters

Cut-Off Voltage

The cut-off voltage used in all tests was 11.7 Volts. This corresponds to the lowest operating voltage for commonly used mobile VHF/UHF amateur radios. For example, the Kenwood TM-V71 specification states that the radio requires 13.8V +/- 15%, which equates to a range of 11.73 to 15.87 VDC.

Duty Cycle Current Values

Duty cycle tests are meant to more closely simulate real world conditions than the constant current discharge tests shown on most battery datasheets. In a duty cycle test, the current is varied between idle, receive and transmit according to the expected duty cycle.

A key test parameter is how much current (or power) to draw from the battery to represent idle, receive and transmit activity. In order to pick meaningful values, the Kenwood TM-V71 dual-band (2m/70cm) mobile radio will be used as representative of common VHF/UHF mobile amateur radios. Current and voltage values from the radio’s user manual and from actual tests were compared.

The Kenwood TM-V71 user manual indicates that the radio will handle an input voltage of 13.8 VDC +/- 15%. This equates to an input voltage range of 11.73 to 15.87 VDC.

The Kenwood TM-V71 user manual is a bit vague regarding the input current requirements. It says "Less than …" for each input current value. This is presumably to account for inrush current, so an appropriate fuse can be chosen. Indeed, the radio is shipped with a 15A fuse in the power cord.

To better understand the steady-state current needs, input current measurements were made at the low, middle and high end of the allowable input voltage range. One might expect that the radio would draw more current at lower input voltages in order to sustain the selected output power. But for the measurements conducted at both VHF and UHF, the worst-case (highest) input current occurred at the highest input voltage in the tested range (15.87 V). The input current also increased slightly the longer the PTT was held down (presumably due to increased heat dissipation). So, all transmit current measurements were made after holding down the PTT for 30 seconds. The test results are summarized in the table below, along with the specifications from the user manual.

Radio Operating State		Current (per User Manual)	Current @ 11.73 V	Current @ 13.8 V	Current @15.87V
Idle					
Squelched, no signal		Not specified	0.5 A	0.5 A	0.5 A
Receive					
@ 2W audio output		"Less than 1.2A"	0.6 A	0.6 A	0.7 A
Transmit					
VHF	Hi (50W)	"Less than 13.0 A"	7.7 A	8.2 A	8.6 A
	Med (10W)	"Less than 5.5 A"	4.6 A	4.6 A	4.7 A
	Low (5W)	"Less than 4.0 A"	3.2 A	3.2 A	3.3 A
UHF	Hi (50W)	"Less than 13.0 A"	8.6 A	9.2 A	9.7 A
	Med (10W)	"Less than 6.5 A"	4.5 A	4.6 A	4.7 A
	Low (5W)	"Less than 5.0 A"	3.1 A	3.2 A	3.3 A

Table 1: Kenwood TM-V71 Current Values

Although the current values do vary based on input voltage, the difference is mostly insignificant, except for when the radio is set to high power. And, at high power, the difference in current used for different input voltages is only about 1 A.

We know that battery voltages will occupy the lower half (11.7 – 13.8V) of the radio's allowable input voltage range. So, current values at the middle of the radio's input voltage range (the 13.8V column above) represent the worst-case current when batteries are the power source.

Since it is generally easier to interpolate than to extrapolate, the duty cycle tests will be based on the worst-case current values from the 13.8V column above. For ease of reference, the current values used in the duty cycle tests are highlighted in the above table. The values for idle and receive are shown in green. The value for 50W transmit is shown in yellow. The value for 10W transmit is shown in orange.

Duty Cycle Time Values

The amount of time spent during the idle, transmit, and receive portions of the cycle will vary, depending on the application. For example, a typical net control will probably spend much more time transmitting than a typical field station. And a typical field voice station will probably spend much more time transmitting than a field packet station. So, the duty cycles for each application will be defined separately.

Battery Capacity

20-hour Rating

Most deep cycle batteries are sold with an Amp*hour (Ah) rating based on a 20-hour test. The 20-hour test was developed as a standard way to compare battery capacity because of the capacity of a lead-acid battery depends on the discharge current.

In the 20-hour rating test, a constant current is used to drain the battery to some terminal voltage over the course of 20 hours. The amount of current it takes to drain the battery to that voltage is multiplied by 20 hours to get the Amp*hour rating.

As an example, the datasheet for the PowerSonic PS-12260 12V 26Ah AGM battery shows the following:

Nominal Capacity

20-hr.	(1.3A to 10.50 volts)	26.0 AH
10-hr.	(2.4A to 10.50 volts)	24.0 AH
5-hr.	(4.4A to 10.20 volts)	22.0 AH
1-hr.	(16.1A to 9.00 volts)	16.1 AH
15-min.	(51A to 9.00 volts)	12.8 AH

The 20-hour rating test uses a constant current of 1.3 Amps to drain the battery down to 10.50 Volts. And that yields (1.3 A * 20 h) = 26 Ah. The other test results in the table make it clear that as the current is increased, capacity is reduced: 24 Ah at 2.4 A, 22 Ah at 4.4 A, etc. This is called the Peukert Effect and is characterized by Peukert's Law, which is discussed below.

Applicability to Amateur Radio Use

While the 20-hour rating is convenient for comparing two batteries of the same type, there are two problems that make it less useful for predicting real-world performance for amateur radio applications:

1. The ending voltage is too low. The 20-hour test in the above example discharges the battery to 10.50 Volts. But a typical amateur radio mobile radio only works down to about 11.7 Volts.
2. The discharge current is too low. The 20-hour test in the above example uses a discharge current of 1.3 Amps. But most amateur radio mobile radios require somewhere in the range of 5-10 Amps of current for transmitting at medium to high power. Even the weighted average of transmit and receive currents typical in an amateur radio environment is usually significantly higher than the current used in the 20-hour test.

Because of the above two factors, the 20-hour is not a good predictor of lead-acid battery performance in an amateur radio environment, at least not directly. A comprehensive review of a battery's datasheet will also reveal that there are several other factors that affect its real-world capacity, such as: temperature, storage time, age, and number of discharge cycles.

Applicability to LFP Batteries

LFP batteries do not suffer the same drop in capacity at higher current levels that lead-acid batteries do. As the test results in this paper will show, LFP batteries deliver about the same capacity at different current levels. Therefore, the 20-hour rating on an LFP can be more easily used to predict performance in the field.

Peukert's Law

The German scientist Wilhelm Peukert developed an equation that approximates the change in capacity of rechargeable lead-acid batteries at different discharge currents. For those who are not interested in the math, it is enough to know that as the discharge current increases, the capacity of the battery decreases. And the relationship is not linear. Doubling the discharge current will reduce the battery capacity by more than one half.

Since the goal is to be able to product the runtime of a given battery in a specific amateur radio application, there are two options:

1. Use Peukert's Law to calculate the expected runtime
2. Establish a "rule of thumb" that produces a "close enough" approximation of the expected runtime

Both approaches will be investigated below. But before that, it is instructive to review the results of some constant current and duty cycle discharge tests.

Constant Current Discharge Test

Overview

A standard discharge test involves drawing a constant amount of current from the battery until a cut-off voltage is reached. This can be repeated for several different current values to produce a family of curves. The curves can be used to get a general understand of the voltage/current/time characteristics of the battery.

Datasheet Values

The AGM battery under test happens to be a PowerSonic model PS-12260. The PowerSonic web site contains some excellent tutorial information and their datasheets provide detailed battery characteristics. So, we use the discharge curves from their model PS-12260 datasheet as representative of what we should expect from a 12 Volt 26.0 Ah AGM battery.

The discharge curves from the PowerSonic PS-12260 26 Ah AGM battery are shown in Figure 1 below. The vertical axis represents Voltage. Time is on the horizontal axis. Each curve represents a different discharge current. Curves for 1.3A, 2.6A, 5.2A, 13A, 26A and 52A are shown.

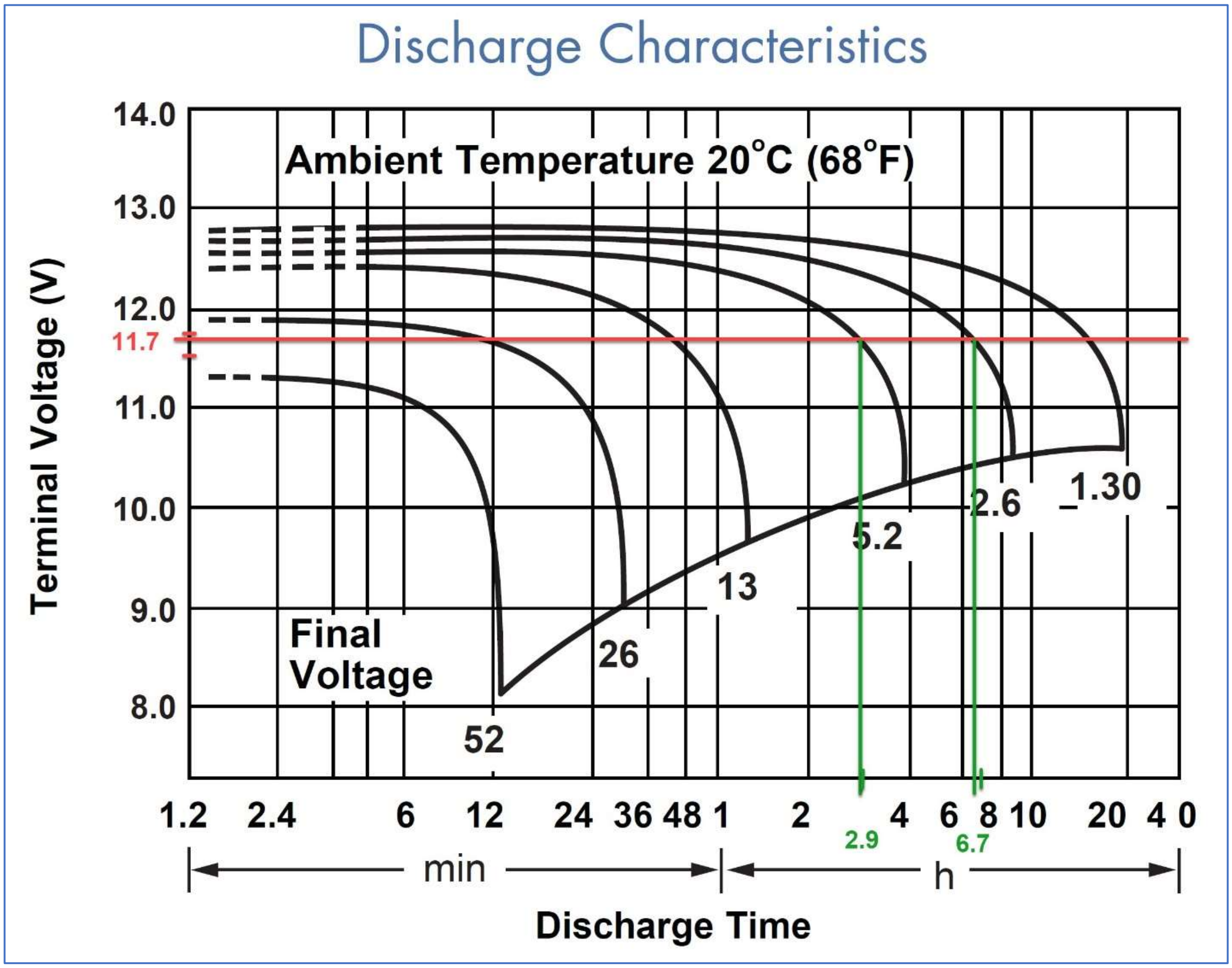


Figure 1: 12V 26Ah AGM Discharge Curves (Source: PowerSonic PS-12260 Datasheet, annotated)

The graph in Figure 1 has been annotated as follows:

- Voltage: Red tick marks have been drawn at approximate 11.5V and 11.75V. A red horizontal line has been drawn at approximately 11.7V, which represents the cut-off voltage of popular VHF/UHF mobile amateur radios.
- Time: Green tick marks have been drawn at approximately 3 hours and 7 hours (note that the horizontal scale is logarithmic). Green vertical lines have been drawn where the 2.6A and 5.2A curves intercept the 11.7V horizontal line. These vertical lines intercept the X-axis at approximately 6.7 hours and 2.9 hours, respectively.

These annotations were made visually, and the resulting values are approximate. In other words, the “Discharge Characteristics” graph from the battery datasheet is representative (an approximation) of the average performance of this model of battery. And the annotations are also approximations. So, the resulting values of 6.7 and 2.9 hours, respectively, are approximations only. Nevertheless, the resulting values provide a reasonable and useful characterization of the expected battery performance.

Based on the above graph, we would expect a brand new, 12V 26Ah AGM battery to last for approximately 6.7 hours (402 minutes) at 2.6A of discharge current, or approximately 2.9 hours (174 minutes) at 5.2A of discharge current. In both cases, the ending voltage will be 11.7V. These are the baseline values against which the two test batteries will be compared.

Test Results

A constant current test was run on both the 26Ah AGM battery and the 20Ah LFP battery. Two current values were used with each battery: 2.6A and 5.2A, corresponding to two of the curves present in the 26Ah battery datasheet. A cut-off voltage of 11.7V was used, corresponding to the low end of the usable voltage range for commonly available mobile amateur radios. The results are shown below.

Note: When comparing the curves below with the curves from the AGM battery datasheet, the time axis in the datasheet is logarithmic, while it is linear in the graph below.

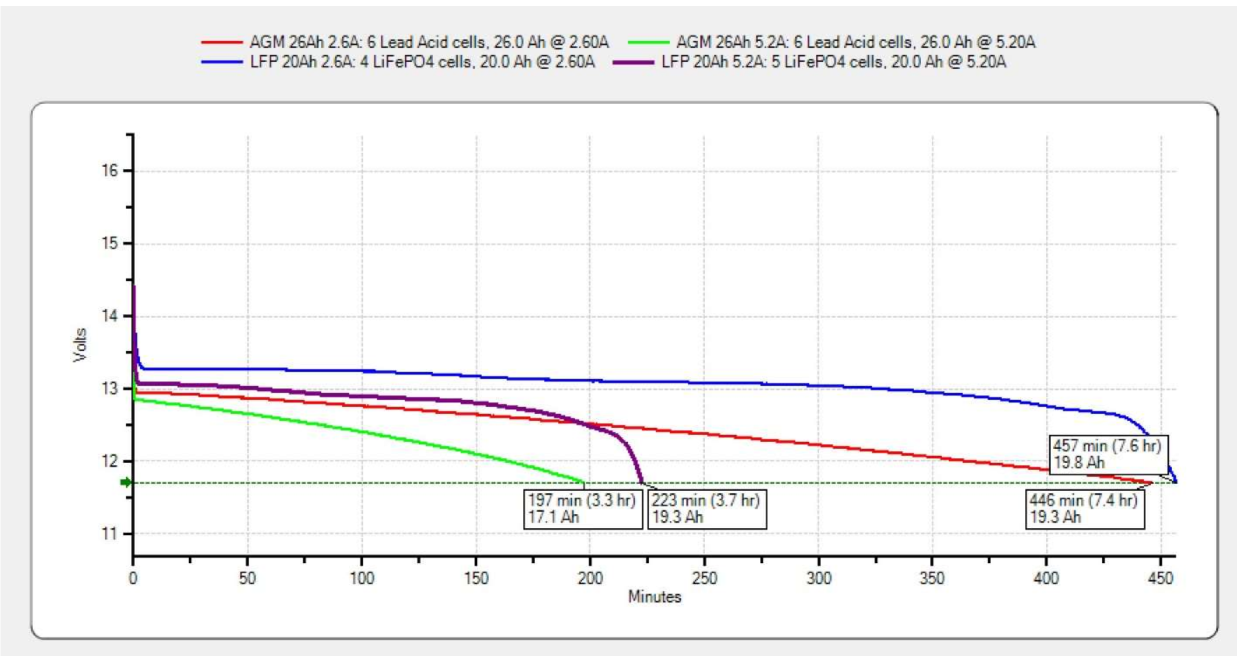


Figure 2: Test results for AGM and LFP Constant Current Discharge Tests at 2.6A and 5.2A

These results can be summarized and compared to the expected values for the 26Ah AGM battery as interpolated from the datasheet.

	2.6A Discharge to 11.7V	5.2A Discharge to 11.7V
26 Ah AGM Datasheet (interpolated)	402 min (6.7 hr); 17.4 Ah	174 min (2.9 hr); 15.1 Ah
26 Ah AGM Battery	446 min (7.4 hr); 19.3 Ah	197 min (3.3 hr); 17.1 Ah
20 Ah LFP Battery	457 min (7.6 hr); 19.8 Ah	226 min (3.8 hr); 19.3 Ah

At the cut-off value of 11.7 Volts needed for amateur radio applications, we can see that the 20 Ah LFP battery provides the same more runtime as the 26Ah AGM battery.

The tests that follow will simulate actual duty cycles for transmit and receive. Their results should provide a more practical assessment of how the batteries would perform in a real deployment environment.

Duty Cycle Tests

Duty cycle tests are meant to more closely approximate real-world conditions by cycling between idle, transmit and receive, and repeating that cycle until the cut-off voltage is reached. The idle conditions is where the radio is not receiving a signal; squelch is closed. The receive condition is when the radio is receiving a signal and outputting audio to a speaker. This requires just slightly more current than the idle condition. Of course, the transmitting condition is when the radio is transmitting at the chosen output power setting.

Each type of position has a different duty cycle. For example, field voice operators spend less time transmitting than net controls. And packet operators spend less time transmitting than field voice operators. The duty cycles for each position are described in detail below. The reader can use the details to decide how representative of their own environment these test might be and interpolate or extrapolate the results accordingly.

Field Operator Duty Cycle Test

Representative Duty Cycle

A representative duty cycle is needed to characterize the battery's performance over the course of a deployment/shift. Some parts of a shift are likely to involve more radio time, such as the beginning of a shift, including set up, check-in, and sending/receiving any messages that have been waiting for the operator to arrive. And some parts of the shift are likely to involve little radio time, such as during steady state management of an event or incident. For purposes of the battery test, the following is assumed to be a representative of the operator's communications over a one-hour period.

- **Total Idle time (no signal received) = 3 minutes (5%)**
  - Even the busiest of nets have some idle time between transmissions, which adds up over the course of an hour
- **Total Transmit time = 12 minutes (20%)**
  - Send two formal messages per hour (ICS-213, ICS-213RR or other form)
    - Clock time = 5 minutes each; 10 minutes total
    - TX time = Approximately 4 minutes each; 8 minutes total
  - Receive two formal message per hour
    - Clock time = 5 minutes each; 10 minutes total
    - TX time = 1 minute each; 2 minutes total
  - Send/receive informal traffic (check-in/out, respond to health and welfare, etc.)
    - TX time = Approximately 2 minutes
- **Total Receive time = 45 minutes (75%)**
  - (60 minutes) – (3 minutes idlet ime) – (12 minutes TX time) = 45
  - Most of the time is spent listening to net control talk to other field operators

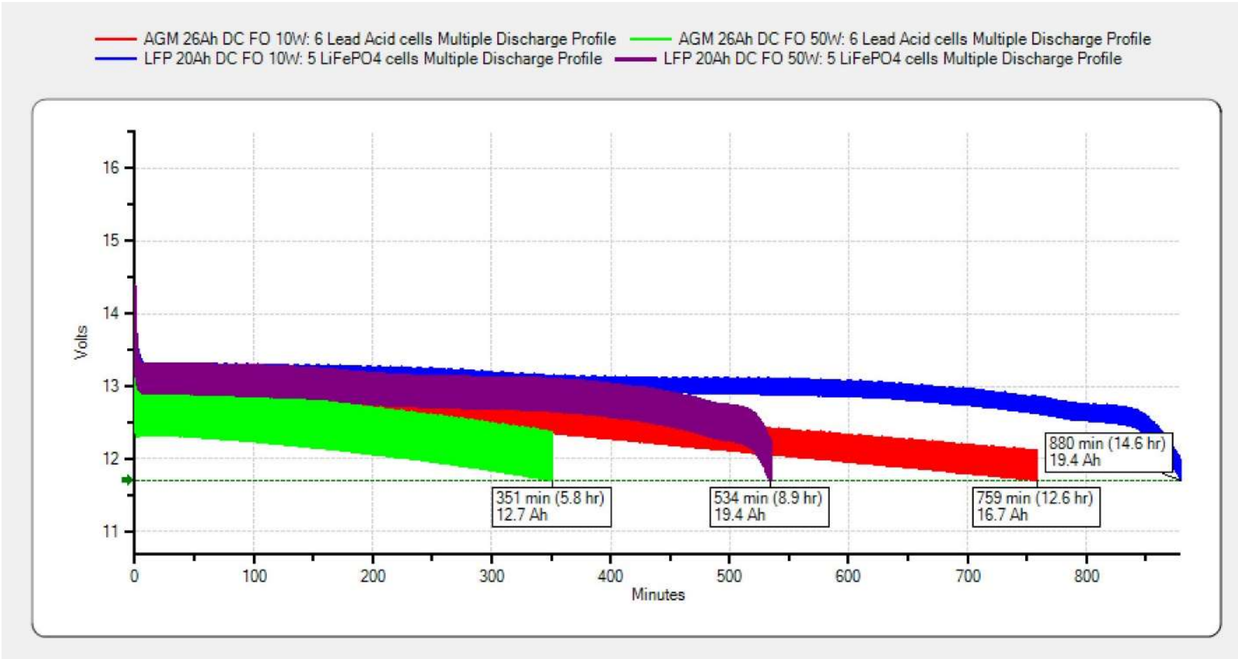
Field Operator Duty Cycle Test Configuration

For each battery, medium (10 W) and high (50 W) transmit power was simulated. The "Multiple Discharge" test was used to simulate a repeating cycle of idle, transmit and receive until the battery reached 11.7 V. The idle, transmit, and receive timing was the same for all tests and was based on the above duty cycle assumptions for a field operator. To better approximate real world switching between transmit and receive, seconds will be substituted for minutes. The current values used were from the previous measurements of the Kenwood TM-V71A. The following table summarizes the test parameters.

State	Duration/Cycle	Medium (10 W)	High (50 W)
Idle	3 sec	0.5 A	0.5 A
Transmit	12 sec	4.6 A	9.2 A
Receive	45 sec	0.6 A	0.6 A

Field Operator Duty Cycle Test Results

The following graph shows the results of all four tests.



These results can be summarized and compared to the expected values for the 26Ah AGM battery as interpolated from the datasheet.

	10 W Transmit	50 W Transmit
26 Ah AGM Battery	759 min (12.6 hr); 16.7 Ah	351 min (5.8 hr); 12.7 Ah
20 Ah LFP Battery	880 min (14.6 hr); 19.4 Ah	534 min (8.9 hr); 19.4 Ah

Net Control Operator Duty Cycle Test

Representative Duty Cycle

A representative duty cycle is needed to characterize the battery's performance over the course of a deployment/shift. Some parts of a shift are likely to involve more radio time, such as the beginning of a shift, including set up, check-in, and sending/receiving any messages that have been waiting for the operator to arrive. And some parts of the shift are likely to involve little radio time, such as during steady state management of an event or incident. For purposes of the battery test, the following is assumed to be representative of a very busy net control operator's communications over a one-hour period.

- **Total Idle time (no signal received) = 3 minutes (5%)**
    - Even the busiest of nets have some idle time between transmissions, which adds up over the course of an hour
- **Total Transmit time = 32 minutes (53%)**
    - Send one formal all stations message per hour (ICS-213, ICS-213RR or other form)
        - Clock time = 8 minutes
        - TX time = Approximately 6 minutes
    - Send four formal messages per hour (ICS-213 or other form)
        - Clock time = 5 minutes each; 20 minutes total
        - TX time = Approximately 4 minutes each; 16 minutes total
    - Receive four formal messages per hour
        - Clock time = 5 minutes each; 20 minutes total
        - TX time = Approximately 1 minute each; 4 minutes total
    - Send/receive informal traffic (conduct two health and welfare checks, net announcements, respond to check-ins/outs, etc.)
        - Clock time = 9 minutes
        - TX time = Approximately 6 minutes
- **Total Receive time = 25 minutes (42%)**
    - (60 minutes) – (3 minutes idle time) – (32 minutes TX time) = 25 minutes

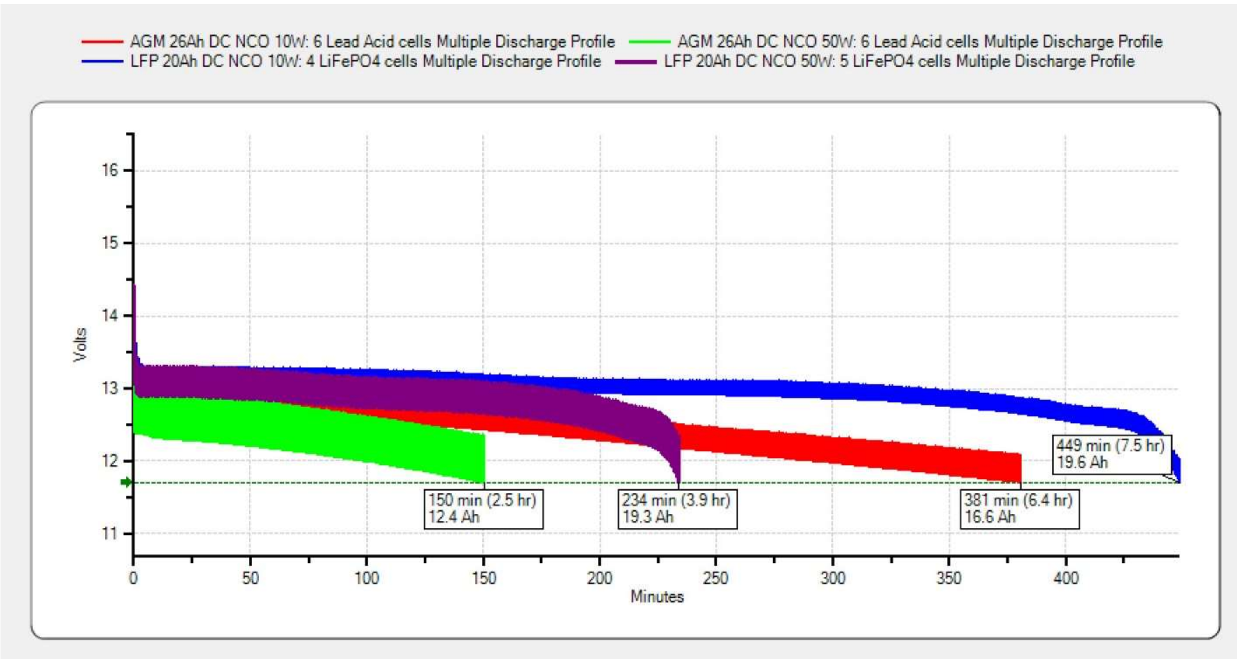
Net Control Duty Cycle Test Configuration

For each battery, medium (10 W) and high (50 W) transmit power was simulated. The "Multiple Discharge" test was used to simulate a repeating cycle of idle, transmit and receive until the battery reached 11.7 V. The idle, transmit, and receive timing was the same for all tests and was based on the above duty cycle assumptions for a net control operator. To better approximate real world switching between transmit and receive, seconds will be substituted for minutes. The current values used were from the previous measurements of the Kenwood TM-V71A. The following table summarizes the test parameters.

State	Duration/Cycle	Medium (10 W)	High (50 W)
Idle	3 sec	0.5 A	0.5 A
Transmit	32 sec	4.6 A	9.2 A
Receive	25 sec	0.6 A	0.6 A

Net Control Duty Cycle Test Results

The following graph shows the results of all four tests.



These results can be summarized and compared to the expected values for the 26Ah AGM battery as interpolated from the datasheet.

	10 W Transmit	50 W Transmit
26 Ah AGM Battery	381 min (6.4 hr); 16.6 Ah	150 min (2.5hr); 12.4 Ah
20 Ah LFP Battery	449 min (7.5 hr); 19.6 Ah	234 min (3.9 hr); 19.3 Ah

Packet Operator Duty Cycle Test

Duty Cycle

Test Results

[To be updated when time permits]

Predicting Battery Capacity

Weighted Average Discharge Current

Calculating an equivalent constant current value from a duty cycle can be done by using the weighted average of the different currents values that make up the duty cycle. The weighted average current can be calculated as follows:

(idle %)(idle current) + (TX %)(TX current) + (RX %)(RX current)

For example, the 50 Watt Field Operator Duty Cycle for one hour can be summarized as follows:

- Idle = 3 minutes (5%) at 0.5 Amps
- Transmit = 12 minutes (20%) at 9.2 Amps
- Receive = 45 minutes (75%) at 0.6 Amps

We can calculate the weighted average current of the 50 Watt Field Operator Duty Cycle to be:

(0.05)(0.5 A) + (0.20)(9.2 A) + (0.75)(0.6 A) = 2.3 A

Rule of Thumb for Battery Capacity

A "rule of thumb" is an approximation that is roughly correct but not intended to be scientifically accurate. It is often used because it's simplicity.

Rule of Thumb for LFP Battery Capacity:

The rule of thumb for calculating expected runtime for an LFP battery can be expressed as:

[LFP 20 hr Rating] / [Weighted Avg Current (A)] = Expected Runtime (hr)

Using this rule of thumb, the expected runtime for the 50 Watt Field Operator Duty Cycle is:

[20 Ah] / [2.3 A] = 8.7 hours

From the Field Operator test results, the actual runtime at 50 Watts was 8.9 hours.

Rule of Thumb for AGM Battery Capacity

The rule of thumb for calculating expected runtime for an AGM battery is similar, but discounts the battery's 20-hour rating by 50%. It can be expressed as:

[50% of AGM 20 hr Rating] / [Weighted Avg Current (A)] = Expected Runtime (hr)

Using this rule of thumb, the expected runtime for the 50 Watt Field Operator Duty Cycle is:

[(0.50)(26 Ah)] / [2.3 A] = [13 Ah] / [2.3 A] = 5.7 hours

From the Field Operator test results, the actual runtime at 50 Watts was 5.8 hours.

Calculating Battery Capacity with Peukert's Law

For those with some basic math skills, Peukert's Law is simple to use and helpful for calculating the expected runtime of a battery for a specific amateur radio application. The law can be written as:

$$t = H\left(\frac{C}{IH}\right)^k$$

where:

H is the rated discharge time (in hours)
C is the rated capacity at that discharge rate (in Amp*hours)
I is the actual discharge current (in Amps)
k is the Peukert constant (dimensionless)
t is the actual time to discharge the battery (in hours)

So, it would seem to be a simple matter of plugging in the rated capacity of the battery and the Peukert constant for that battery, along with the expected actual current, in order to calculate the expected runtime. But remember that the 20-hour test rating for most batteries involves running the battery down to a much lower voltage than most amateur radios will tolerate. So, two steps are required before Peukert's law can be used:

1. Determine a new capacity rating which incorporates the 11.7 cut-off voltage
2. Determine Peukert's constant for the battery in question

Determining Battery Capacity with an 11.7 Volt Cut-off

Determining Peukert's Constant

Some typical values for Peukert's constant, *k* are:

1.00: ideal battery; capacity is independent of current
1.01 or less: $LiFePO_4$ battery
1.05 – 1.15: AGM lead-acid battery
1.10 – 1.25: Gelled lead-acid battery
1.20 – 1.60: Flooded lead-acid battery (automotive starter batteries)