Testing of Commercially Available USB-Rechargeable Single-Cell Batteries to Inform Military Applications

Calvin Y. Duong
C5ISR Center
U.S. Army Combat Capabilities Development Command
Aberdeen Proving Ground, MD, USA, 21005
calvin.y.duong.civ@army.mil

Abstract

Single-cell batteries that can be recharged through a Universal Serial Bus (USB) connector are commercially available in the same form factors as AA, CR123, 18650, and 21700 cells. Forty brands of these batteries were purchased and studied to inform development of a militarized version, known as the Operational Single-Cell for Accessory Readiness (OSCAR) battery for increased safety, reduced weight burden, and simpler logistics compared to loose cells. This paper presents the results of cycle testing and other observations about the batteries, such as USB connector location, overcurrent protection, overdischarge protection, and identical designs. No destructive testing was performed. Due to page limitations, only the AA batteries will be discussed in this paper.

Keywords

USB; rechargeable; single cell; batteries; cycle testing

Introduction

For military applications, switching to rechargeable batteries would simplify logistics because the same batteries could be recharged and reused, unlike primary cells which need to be constantly resupplied after they are used. Discarded primary cells contain a significant amount of energy most of the time, which is a waste of energy. With rechargeables, leftover energy could be stored and used after the next recharge. Loose cells have a safety risk of being short circuited without protection whereas a proper battery would have a battery management system (BMS) to protect itself from faults.

Because of the possible benefits of single-cell rechargeable batteries, a military version is being developed, known as OSCAR. To learn what goals and metrics OSCAR should meet, a market survey was performed. The study specifically focused on USB-rechargeable batteries because of the interoperability and ease of charging that USB enables. Among the metrics studied were energy capacity, USB connector type and position, and state of charge indicator. Further details are described in the next section.

Methods

Commercial off-the-shelf (COTS) batteries were purchased from Amazon and a few other websites in 2021 (Figure 1). As many brands as possible were purchased for this study.

Figure 1. Boxes of some COTS USB-rechargeable single-cell batteries that were purchased for the study.

To automate the cycling of these batteries, a test stand was built. It can simultaneously cycle up to six cylindrical batteries that can be recharged through a USB connector. It consists of:

- One (1) USB hub to charge batteries (Figure 2)
- Six (6) e-loads to discharge batteries (Figure 2)
- Six (6) thermocouples to monitor temperature (Figure 2)
- A box to facilitate cable connections and hold up to six (6) batteries (Figure 3)

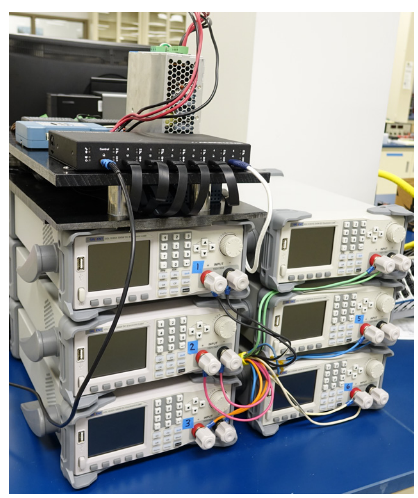

Figure 2. Part of the test stand used for this study. Includes the e-loads, USB hub, and thermocouple reader.

Figure 3. The box that held the batteries that were tested.

Voltage and current are continuously measured through the USB hub and e-loads. Everything is controlled with LabVIEW.

One battery of each brand was cycled with the OSCAR test stand. Primary cells were also discharged for comparison with rechargeable batteries but only for the AA and CR123 sizes.

To go through all brands quickly throughout 2022, each battery was cycled for **up to 10 cycles**. (Primary cells could only be discharged once. Technical difficulties with the OSCAR test stand reduced the planned number of cycles for some brands.) All charges were subject to the battery's battery management system (BMS). That is, 5 V was provided to the batteries, as per the USB standard, while the current was controlled by the BMS. All discharges were at a **constant power of 0.5 W**. The Watt-hour results that are shown in Table 1 are **averaged across all cycles**. There was a five-minute rest period between charges and discharges.

Results

For cycling results, see Table 1 on the next page.

Discussion – Cycling

Energy Capacity: **Almost all batteries have less energy capacity (Wh) than advertised** when discharged at a constant power of 0.5 W. (See all the red or negative signs in the Difference Wh column of Table 1.) Primary cells also had lower capacity than advertised, but their datasheets explained that the capacities were obtained from a constant current discharge of 100 mA [1][2]. The difference in capacities can be explained by the different discharge conditions. For the rechargeable batteries, it is unclear under what conditions they derived the capacities that were advertised.

Rechargeable Capacity vs. Primary Capacity: As of 2022, **COTS USB-rechargeable batteries do not have more energy capacity** for a single discharge **when compared to primary lithium cells of the same form factor**. Only AA and CR123 primary cells were tested. This is important because it is a potential drawback of going from primary cells to rechargeable batteries.

USB Connector: For AA batteries, the USB connector type, location, and orientation combinations are ranked below from highest to lowest energy capacity:

1. Micro-B, side, horizontal
2. Micro-B, top
3. USB-C, side, horizontal
4. Micro-B, side, vertical

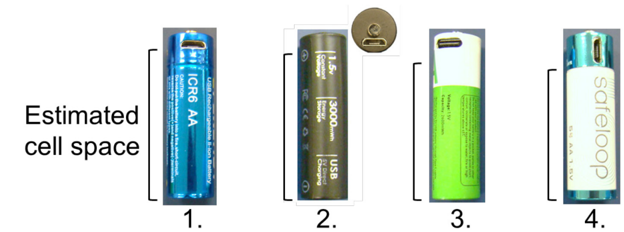

Figure 4. An example of each kind of USB configuration with a bracket drawn to show the estimated space for a cell.

Figure 5. A disassembled Micro-B/side/vertical battery. The cell and PCB at the top-right show how much space the circuitry takes up.

It is thought that the reason for this order is because the USB configuration that takes up the least space in the can provides more space for a bigger cell, resulting in a higher capacity (Figure 4). USB Micro-B receptacles are smaller than USB-C receptacles. This leaves more space on the printed circuit board (PCB) to fit all necessary components without using additional PCBs. Thus, the Micro-B/side/horizontal configuration would allow the most space for a cell. Micro-B/top is a close second. Turning the receptacle at right angle to board would give more room for components on the PCB compared to Micro-B/side/horizontal, but the receptacle would take up more of the can's height. USB-C came in third because a USB-C receptacle takes up almost all of one side of a circular AA-sized PCB. There would need to be multiple PCBs to fit all components, which takes up more height. Finally, Micro-B/side/vertical is the worst because it wastes a lot of space by turning the USB connector and the entire PCB sideways (Figure 5).

Table 1. List of AA batteries purchased, their descriptions, and average energy capacity results from cycling.

	USB			Advertised			Results	
Brand	Type	Location	Orientation	V	Ah	Wh	Actual Wh	Difference Wh
Energizer Ultimate Lithium (L91)	Primary	-	-	1.5	3.50	5.25	4.24	-1.01
Epoch	Micro	Side	Horizontal	1.5	2.30	3.45	3.17	-0.28
CT-Energy	Micro	Side	Horizontal	1.5	2.33	3.50	2.95	-0.55
Keeppower	Micro	Side	Horizontal	1.5	2.26	3.39	2.86	-0.53
Nitecore	Micro	Side	Horizontal	3.6	0.75	2.70	2.80	0.10
Skylaxy	Micro	Top	-	1.5	1.85	2.78	2.58	-0.20
Pownergy	Micro	Top	-	1.5	1.97	2.96	2.57	-0.39
Fenix	Micro	Side	Horizontal	1.5	1.60	2.40	2.57	0.17
EBL	Micro	Side	Horizontal	1.5	2.20	3.30	2.56	-0.74
Tipsun	Micro	Side	Horizontal	1.5	1.30	2.80	2.53	-0.27
Fuvaly	Magnetic	Top	-	1.5	2.00	3.00	2.49	-0.51
AmpTorrent	Micro	Top	-	1.5	1.97	2.96	2.42	-0.54
Naccon	Micro	Side	Horizontal	1.5	1.60	2.40	2.23	-0.17
Bluerise	Type-C	Side	Horizontal	1.5	1.70	2.55	2.21	-0.34
Tinoteen	Type-C	Side	Horizontal	1.5	1.73	2.60	2.11	-0.49
Maxwel	Type-C	Side	Horizontal	1.5	1.73	2.60	2.04	-0.56
JWWYJ	Type-C	Side	Horizontal	1.5	1.70	2.55	2.01	-0.54
Anvow	Type-C	Side	Horizontal	1.5	2.27	3.40	1.96	-1.44
Lankoo	Type-C	Side	Horizontal	1.5	1.73	2.60	1.89	-0.71
Vivitar	Type-C	Side	Horizontal	1.5	1.60	2.40	1.77	-0.63
Uzone	Type-C	Side	Horizontal	1.5	1.73	2.60	1.75	-0.85
Deleepow	Micro	Side	Vertical	1.5	1.87	2.80	1.54	-1.26
Fuvaly	Micro	Side	Vertical	1.5	1.50	2.25	1.40	-0.85
Bump	Micro	Side	Vertical	1.5	1.20	1.80	1.40	-0.40
Sorbo	Type-A Male	Top	-	1.5	1.20	1.80	1.39	-0.41
Safeloop	Micro	Side	Vertical	1.5	1.25	1.88	1.21	-0.67
PaleBlue	Micro	Side	Vertical	1.5	1.56	2.34	1.18	-1.16
Energizer Alkaline Power	Primary	-	-	1.5	1.00	1.50	0.76	-0.74

This is the only USB configuration in which the PCB is not a circular cross-section of the can.

Discussion – Other Observations

No State of Charge Indicators: No batteries (not even larger sizes, such as 18650 or 21700) have a state of charge indicator. They only have indicators to show whether the battery is charging or full. State of charge indicators would allow users to know how much energy is left in the batteries and plan accordingly.

Identical Designs: Based on the type and placement of charging indicator light-emitting diodes (LEDs), it is probable that groups of certain brands share the exact same designs. The only way to be sure would be to take the batteries apart, but most were not disassembled for safety reasons. They are too suspiciously identical to be a coincidence. The implications are unclear. This could mean some brands may be owned by the same parent company, or intellectual property is not well-protected in some other countries.

This is interesting because it reduces the number of unique designs on the market. Out of 26 AA brands, there are just seven types of designs plus three truly unique designs. The most obvious cases of copied designs are shown in Figure 6 through Figure 9. (These pictures are best viewed in color. The captions also describe position based on an hour hand's position on a clock.)

Overcurrent Protection: Batteries had some form of overcurrent protection, but it was not fully effective. With an e-load in constant power mode, the power was increased in 0.1-W steps until the battery's voltage dropped to near zero. This usually happened when the current exceeded 1

A. The current then dropped to around 300 mA, which is still a substantial amount of current.

Figure 6. Though these look like three batteries from the same brand, they are actually three different brands. They all have a red charging LED at the 3:00 position that turns green when fully charged.

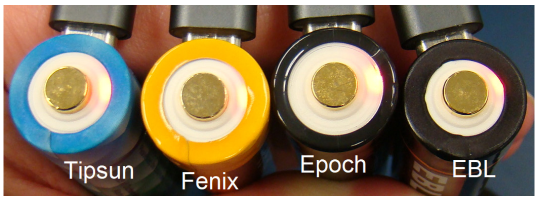

Figure 7. Batteries that have a red LED at 3:00 that turns blue when fully charged. They have the same positive contact material, and the LEDs are half covered with the edge of the label.

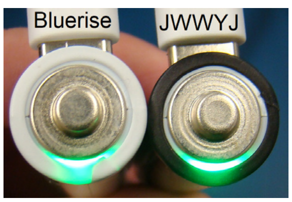

Figure 8. Batteries that have a blinking green LED that shines through a crack at 6:00. The LED remains on when fully charged.

Figure 9. All USB-C batteries had a red LED that blinks through the USB-C connector when charging. The LED stays on when fully charged.

Overdischarge Protection: There were overdischarge problems with some batteries which continued to discharge a significant amount of current even though the voltage was close to zero. Zero voltage is a sign that the battery was trying to disconnect from the load, but it could also be an artifact of the e-load being set to constant power mode. The e-load could have been shorting the battery to draw more current to maintain a power of 0.5 W. Either way, the overdischarge protections do not seem to work for some batteries, as seen in Figure 10, which shows the most extreme case. There was an associated temperature spike from 27°C to 30°C.

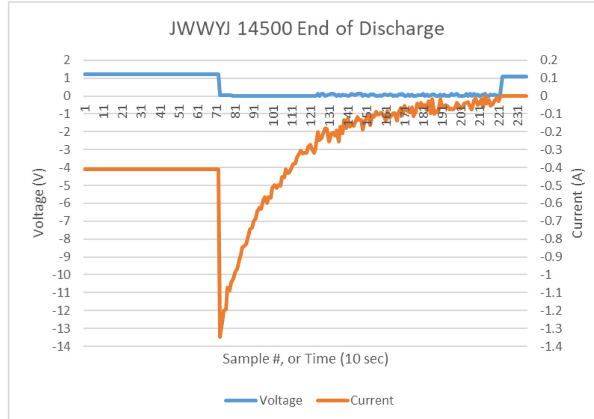

Figure 10. The JWWYJ brand battery at the end of a discharge. The top curve shows the voltage drops to zero. The bottom curve shows the current spikes to 1.4 A (negative because of the chosen convention) and exponentially decays to zero over the next 25 minutes. When the load is turned off, the voltage recovers to 1.1 V.

Caution when Charging and Using Simultaneously: Roughly half of these AA batteries have 5 V across the ends of the battery while charging, which suggests that they are connected directly to the USB connector's V_{BUS} and GND pins. For this reason, the batteries should not be charged while they are being used in a device because the 5 V could break devices that are expecting only 1.5 V.

Conclusion

The COTS USB-rechargeable single-cell batteries generally function as promised. They can all be charged with a standard USB cable and discharged through the anode and cathode as claimed. However, cycle testing revealed that the batteries had lower energy capacities (Watt-hours) than advertised, with five exceptions (only two AA batteries). There are just a few unique designs; multiple brands showed indications of sharing the exact same mechanical and electrical design. The overcurrent protection in the AA batteries functions to some extent by reducing the current and preventing thermal events. For some AA batteries, overdischarge protection is not effective at stopping further current from exiting the battery while it is still connected to a load.

Acknowledgements

The author would like to thank Dr. Nathan Sharpes and intern Sam Floyd for their assistance with this work.

References

1. Energizer L91 Ultimate Lithium datasheet, https://data.energizer.com/pdfs/l91.pdf
2. Energizer LR6 Alkaline Power datasheet, https://data.energizer.com/pdfs/alk-power-aa.pdf