Portability and Performance of Battery Chemistries in Applied Robotics

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AP Research

Introduction

Battery technology has been a cornerstone of technological breakthroughs in the last decade. The increase of power density and portability means that more can be run portably, increasing the power of portable applications.

I am the captain of a FIRST Tech Challenge (FTC) robotics team. The robots we build get more and more complicated and heavy each year, requiring greater amounts of energy from our batteries powering them. In our competitions, we are only allowed to use a medium capacity NiMH battery to power our robot ("ROVER RUCKUS Game Manual Part 1", 2018, p.30). Consequently, it is very easy to overwhelm a robot's battery just during the two and a half minutes of each match. A robot battery is rated for about 3000mAh, meaning it will ideally last three hours under a load of 1 amp. However, legal batteries are rated to a maximum of 30 amp discharge internally, and externally limited by a 20 amp fuse. This means that that under full load, a battery can be fully discharged in around 4 minutes ("Battery Life Calculator", 2019), and drop to a low enough voltage to shut the robot off in the span of a match under heavy load, which has occurred on a regular basis during competition. Other robotics competitions like VEX Robotics Competition (VRC) are now allowing use of lithium-based batteries ("2018-19 VEX Robotics Robotics Game", 2018; "V5 Robot Battery", n.d.), which still provide ample power to the robots, even when undercharged and under load. New battery chemistries are always in demand to grow with the ever-developing requirements of competitive robotics (Massengill & Schreiber, 2018).

Purpose

The purpose of this research is to explore the viability and costs and benefits associated with moving to a more modern battery chemistry in competitive robotics. This research will include the evaluation of a battery chemistry's "portability" and viability of use in a robotics application: such factors considered include safety, cost, power capacity, density, and weight.

This research will also be used to explain the advantages and disadvantages of specific types of batteries to robotics teams, parts suppliers, hobbyists, as well as the FIRST Game Design Committee to evaluate a possible new battery technology and its implementations in competitive robotics.

Research Questions

The questions this study seeks to answer are:

- What battery chemistry is most effective for an applied robotics application?
- What factors are involved in deciding the portability and usefulness of a battery?
- How do we quantitatively measure one battery to another?
- How can we measure how safe a battery is?
- How effectively can a new battery chemistry be implemented to existing applications, and what are its drawbacks, if any?

Theoretical Framework

The University of Cambridge lists many factors must be taken into account when choosing a battery for an application. These include Voltage, Discharge curve, Capacity, Energy density, Specific energy density, Power density, Cost, and Application requirements (University of Cambridge, n.d.). The definition of these variables will be used to factor in the portability of each battery chemistry and design, but we will mainly focus on the performance aspects of the battery. In a competitive robotics application, for example, something like temperature sensitivity would be not very useful to look at, due to the fact that most competitions are held indoors with no risk of overheating or freezing.

This study will be a quantitative study. There are both quantitative and qualitative elements to this study, for instance, the specific state of a battery after it has been damaged isn't directly quantifiable, but using standards we can convert the damage that occurred and the reaction into a quantitative measurement.

Batteries will be tested inside of a competition FTC robot to simulate a competition use-case. For reference, an FTC robot is limited to a maximum of 8 motors, 12 hobby-grade servos, and cannot exceed a weight of 42 lbs ("ROVER RUCKUS Game Manual Part 1", 2018, p.40). Much like small-scale radio control cars, an FTC robot is made up of those same parts with approximately the same power draw, per motor. From empirical testing, simply driving around can draw 5-6 amps from a competition robot's battery ("Andymark Neverest", n.d.), due to the use of anywhere from 2 to 4 motors on the drivetrain. Additionally, a battery can go anywhere from 1-4 matches on a single charged battery before requiring it to be swapped, based on previous robot designs. A battery tester will take specific measurements of battery power and discharge rate. This battery tester will also measure internal resistance, a metric that determines not only how much current a battery can discharge, but also how much it heats up.

Safety will be evaluated through destructive testing of the batteries and evaluated through EUCAR guidelines on a scale of 0 - 7 (Ashtiani, 2008). This ranges from no change in functionality, to explosion.

Table 2 . Severity Levels (Adopted and modified from EUCAR)

S	Description	Criteria for Severity Classification & Effects
0	No effect	No effect. No loss of functionality.
1	Reversible Loss of Function	No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Temporary loss of battery functionality. Resetting of protective device needed.
2	Irreversible Defect/Damage	No leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. RESS irreversibly damaged. Repair needed.
3	Leakage Δ mass < 50%	No venting, fire, or flame; no rupture; no explosion. Weight loss <50% of electrolyte weight. Light smoke (electrolyte = solvent + salt).
4	Venting Δ mass >= 50%	No fire or flame; no rupture; no explosion. Weight loss >=50% of electrolyte weight. Heavy smoke (electrolyte = solvent + salt)
5	Fire or Flame	No rupture; no explosion (*i.e.,* no flying parts).
6	Rupture	No explosion. RESS could disintegrate but slowly without flying parts of high thermal or kinetic energy
7	Explosion	Explosion (*i.e.,* disintegration of the RESS with externally damaging thermal & kinetic forces). Exposure to toxic substances in excess of OSHA limits

Figure 1: Modified Severity Levels chart from EUCAR standards, to evaluate safety.

Methods

This data will be used to synthesize a cost-benefit analysis of each battery chemistry and its application in competitive robotics. Additionally, the weight and volume of the battery will be accounted for; a significant portion of robot design can be attributed to designing around the battery (Digby, 2013), and thus heavier and bulkier batteries will leave some teams at a disadvantage for both total weight capacity and internal space.

Runtime and power curves will be calculated through running a battery through a fixed load until the battery reaches 8 volts, which is the specified shutoff voltage of the REV Robotics Expansion Hubs used on our robot ("FTC Robot Sample Wiring Diagram", 2019), or when the battery reaches its minimum safe working voltage, which is 10v for the LiFePO4 battery and 9v for the LiPo battery ("K2 26650 LiFePO4 Datasheet", n.d.; "BU-107: Comparison Table of Secondary Batteries", n.d.). The load in question will be 5 amps and 10 amps. The advantage to having a dynamic load setup rather than a set ohmic load is that power draw will not decrease over time. A constant load test setup will be built to the specifications listed in Kerry D. Wong's schematic (Wong, 2013). Voltage over time will be graphed until the minimum voltage is reached to generate capacity curves. Two batteries of each chemistry will be measured, and their results will be averaged. This makes sure that no defective batteries or outliers significantly affect the measurement data and comparison.

Safety testing will be conducted by a special fixture in a fumehood used to physically breach and electrically short each of the batteries to evaluate safety in case of accidental damage to the batteries. Many hazard modes are present when considering how to test a battery, but in this case it will be tested through nail intrusion and short circuit (Ashtiani, 2008). Analysis of failure mode, such as if the battery leaks, sparks or flames will be used to draw a conclusion of safety, as well as using the EUCAR listed guidelines to quantify the battery reaction to damage. This allows us to quantify the safety of each battery and compare it to one another.

Battery characteristics, such as internal resistance, state of charge, and discharge rate, will be calculated through specialized tools. These measurements will be averaged and plotted to give a per-chemistry view, to accurately compare each of the battery chemistries and their main electrical properties. Other factors like power-to-weight and power-to-volume will be manually calculated through weighing and measuring the battery in its final form, with applicable Battery Management System attached. This will allow for both quantitative and qualitative data to be factored in the consideration of each battery chemistry in portable applications.

The minimal risks of this research include physical ingress of batteries and is potentially hazardous if battery acid or noxious fumes are released. This risk will be mitigated through the use of lab safety protocols, including an isolated fume hood to vent and contain all respiratory and skin irritants. Additionally, accidental damage to a battery is possible, but short-circuit protection is handled by a mandatory fuse installed inline with the battery and the testing apparatus.

Battery Selection

A battery in its simplest form is any kind of chemical reaction that creates a voltage, usually with metals such as lithium, nickel or zinc (“BU-104b: Battery Building Blocks”, n.d.). Most batteries are denoted by their cathode material or chemical make-up. The batteries tested in this study will be the most common, commercially-available battery chemistries that are comparable to the already-legal batteries used in the FTC competition. The batteries tested in this study will be of the following voltages, chemistries, and capacities (see fig.2).

Chemistry	Nom. Voltage	Nom. Volts/cell	Capacity	Volume	Weight	Price
Pb	12v	2v	3400mAh	0.511 L	1265.2g	**$15.99**
NiMH	12v	1.2v	3000mAh	0.226 L	610.4g	$49.99
LiFePO4	12.8v	3.2v	3200mAh	0.222 L	336.7g	~$30
LiPo	11.1v	3.7v	3000mAh	**0.073 L**	**241.8g**	$21.99

Figure 2: Table of tested batteries and their manufacturer specifications.

The rationale behind this specific selection of batteries is to try to as closely replicate the nominal voltage and capacity of an already-legal NiMH battery. A NiMH battery has a nominal cell voltage of 1.2 volts/cell; it requires 10 cells in series to get a nominal voltage of 12 volts. The working voltage of this battery, however, may exceed 14 volts depending on the charger used. A lead-acid battery is a nice analogue to a NiMH in this case, as its 2v/cell nominal means it gets to the same nominal and working voltage. However, the problems arise when trying to find comparable lithium counterparts. Not only do the voltages not directly compare for either chemistry, but finding a commercially available LiFePO4 that was rated for this application was impossible. A 3S (**3** cells in **s**eries) lithium polymer battery, and a custom built 4S (**4** cells in **s**eries) lithium-iron-phosphate battery was used. The working voltage of a 3S LiPo is approximately 12.6 volts (4.2 volts/cell), and the working voltage of a 4S LiFePO4 battery is approximately 14.8 volts (3.7 volts/cell), both capped by the charging circuitry of the TB6B charger. This was decided upon because it gives a comparable range of battery voltages, without having to use external circuitry like a boost converter to change the voltage. This significantly decreases the cost associated with the battery or control system and creates a close analogue to what is already available in these applications.

Additionally, a hard limit of 15v working voltage was put into place as a design consideration. Many motor controllers and electronics only use 15-16v rated capacitors, the REV Expansion Hub used in FTC included, so a 4 cell lithium-polymer battery at a charged voltage of 16.8v would damage existing components or require a redesign of existing hardware, increasing the already visible cost of replacing a battery.

Specifications	Lead Acid	NiCd	NiMH	Li-ion[1]		
				Cobalt	Manganese	Phosphate
Specific energy (Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120
Internal resistance	Very Low	Very low	Low	Moderate	Low	Very low
Cycle life[2] (80% DoD)	200–300	1,000[3]	300–500[3]	500–1,000	500–1,000	1,000–2,000
Charge time[4]	8–16h	1–2h	2–4h	2–4h	1–2h	1–2h
Overcharge tolerance	High	Moderate	Low	Low. No trickle charge		
Self-discharge/ month (room temp)	5%	20%[5]	30%[5]	<5% Protection circuit consumes 3%/month		
Cell voltage (nominal)	2V	1.2V[6]	1.2V[6]	3.6V[7]	3.7V[7]	3.2–3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20 typical Some go to higher V		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75V	1.00V		2.50–3.00V		2.50V
Peak load current Best result	5C[8] 0.2C	20C 1C	5C 0.5C	2C <1C	>30C <10C	>30C <10C
Charge temperature	–20 to 50°C (–4 to 122°F)	0 to 45°C (32 to 113°F)		0 to 45°C[9] (32 to 113°F)		
Discharge temperature	–20 to 50°C (–4 to 122°F)	–20 to 65°C (–4 to 49°F)		–20 to 60°C (–4 to 140°F)		
Maintenance requirement	3–6 months[10] (toping chg.)	Full discharge every 90 days when in full use		Maintenance-free		
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory[11]		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic efficiency[12]	~90%	~70% slow charge ~90% fast charge		99%		
Cost	Low	Moderate		High[13]		

Figure 3: All tested batteries and their characteristics excluding Li-ion Cobalt. ("BU-107: Comparison Table of Secondary Batteries", n.d.)

Battery Building

Out of the four battery chemistries listed, three were readily available and inexpensive at this specification. The tested lead-acid battery is a generic, 12v 3400mAh AGM (sealed lead-acid) battery. The tested nickel-metal hydride (NiMH) battery is the FTC competition legal and available Tetrix 12v 3000mAh NiMH battery. The tested lithium-polymer battery is a generic 11.1v 3000mAh 3s LiPo battery pack. However, for the LiFePO4 battery pack, there were a few problems. First, there were few commercial offerings for the specific battery analogue (12v, 3000mAh, capable of at least 20A discharge). Most of them met the voltage and capacity specifications but were limited to under 10 amps discharge current. Second, they were mostly custom-built packs or required import. And third, it was relatively price prohibitive to get a pack that didn't even meet the discharge specifications.

For testing, a 4S LiFePO4 battery was assembled, with battery management system (BMS), through parts ordered online. Price was one factor in the consideration of battery usage, so price was kept down intentionally. The cells tested are K2 Energy 3200mAh, 26650 cells, rated for a peak 28 amps of discharge. Bulk packs of 20 cells are available online for around $62 including shipping. The BMS was purchased for $7. In this form, it represents the closest analogue to the form factor of the NiMH battery, at a comparable weight, and will be used to factor in the cost comparison of the batteries.

Figure 4: The battery chemistries used for testing. Top Left: Lead Acid, Top Right: NiMH, Bottom Left: LiFePO4, Bottom Right: LiPo

All battery chemistries had their own unique cell shapes available (see fig. 4). The commercially available NiMH cells were all cylindrical, and the lead-acid cells are all permanently arranged in a large plastic casing. All lithium chemistries were available in both pouch format and cylindrical cells; however, there is one key difference. Substituted for a standard “Li-Ion” battery was a “LiPo” (lithium polymer) battery. The difference between these, in fact, is surprisingly little: “In short, it means that so-called ‘lithium-polymer’ batteries are almost exactly the same as lithium-ion batteries, but they are instead contained in a flexible polymer casing. It’s basically just a repackaged lithium-ion battery” (Ogrin, 2015). It was much easier to source a lithium-polymer battery than an equivalent lithium-ion battery, so a lithium-polymer battery was used for the test results.

Load Tester

The load tester was originally designed to be a 0.75ohm fixed resistance load that would dissipate the battery's energy through a bank of resistors. However, due to Ohm's law, when the voltage of the battery would decrease under load, the total watt load would naturally decrease, and thus the battery voltage and load would slowly taper off instead of being fully loaded (GreatScott!, 2017). While this may be more indicative of what a robot might see when its motors are stalled, the most accurate way to compare these batteries and their discharge characteristics would be using a load tester that would apply a constant power draw, increasing the amps drawn as the voltage decreases. A load tester was built to the specifications of Kerry D. Wong's guide on an adjustable, microcontroller-based load tester that will accurately do Constant Current and Constant Power draw for testing (Wong, 2013). Power MOSFETs were used to convert the amperage drawn into heat, which was then exhausted by a fan on a heatsink (see fig. 5). The software was modified to allow voltage logging on a computer for data analysis.

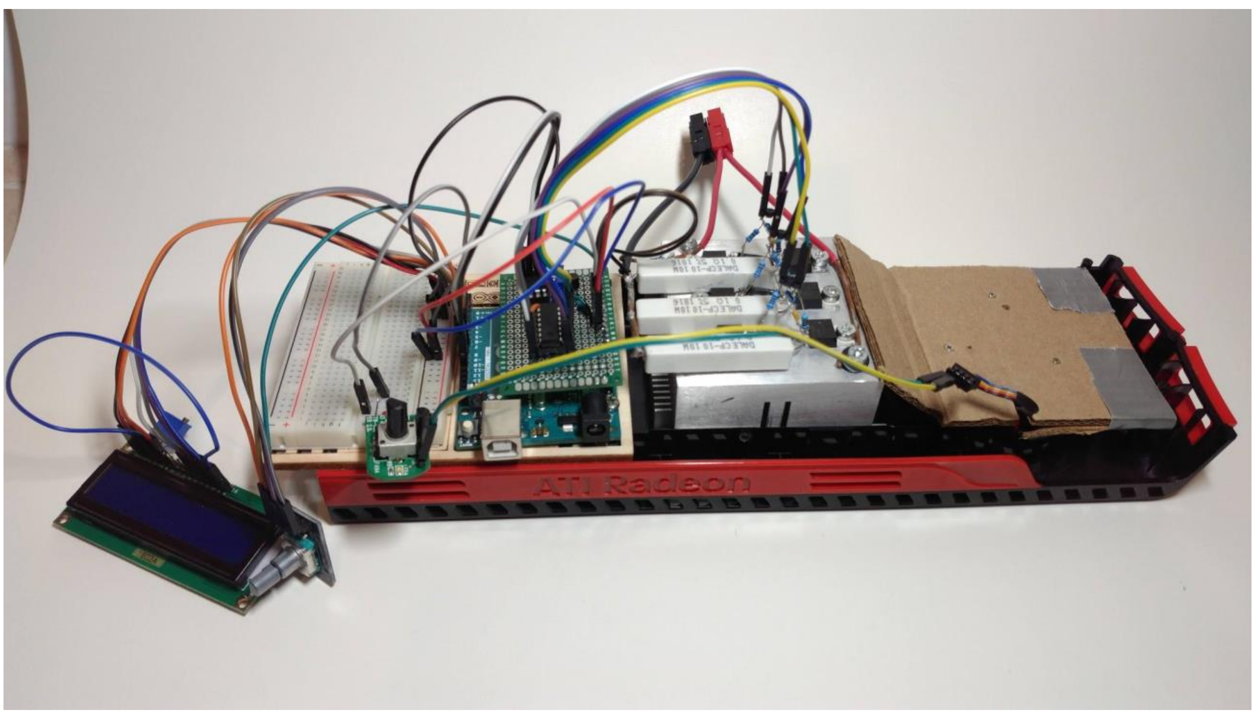


Figure 5: The adjustable load used to test batteries.

Internal Resistance Testing

Measuring the internal resistance of a battery is a key aspect in comparing batteries and different chemistries. In an ideal world, a battery would have an internal resistance of 0 ohms, meaning that it could deliver infinite amounts of current and the battery would not drop any voltage. However, since batteries are not perfect, they will all have some kind of internal resistance, usually in the milliohm range (“BU-802a: Rising Internal Resistance”, 2016). Having an internal resistance means that the battery will drop voltage under load, it will generate heat inside itself under load, and that there is a maximum load that can be drawn from the battery. Measuring this value means that theoretically simulating the battery is possible.

There are three ways of measuring the internal resistance of a battery: DC Load, AC Conductance, and Electrochemical Impedance Spectroscopy (EIS) (“Introduction to Electrochemical Impedance Spectroscopy”, n.d.; “BU-902: How to Measure Internal Resistance”, 2017). It will not be practical to measure with EIS in this study, since it requires very expensive equipment and a lot of complex calculations, so the two possible methods are DC Load and AC Conductance. DC Load Calculation measures the change in battery voltage by using a set load, and then calculating the resistance inside the battery. AC Conductance Calculation injects a 1000Hz AC wave into the battery to measure the combined resistance and capacitance. It was decided to use the AC Conductance method because it was much simpler and provided a more accurate measurement than achievable with just measuring with resistors and Ohms law. This is also a standard form of measurement that is found on most manufacturer datasheets for batteries and battery cells and will not vary significantly unlike DC Load resistance measurement. The meter used is a YR1030 (see fig. 6)

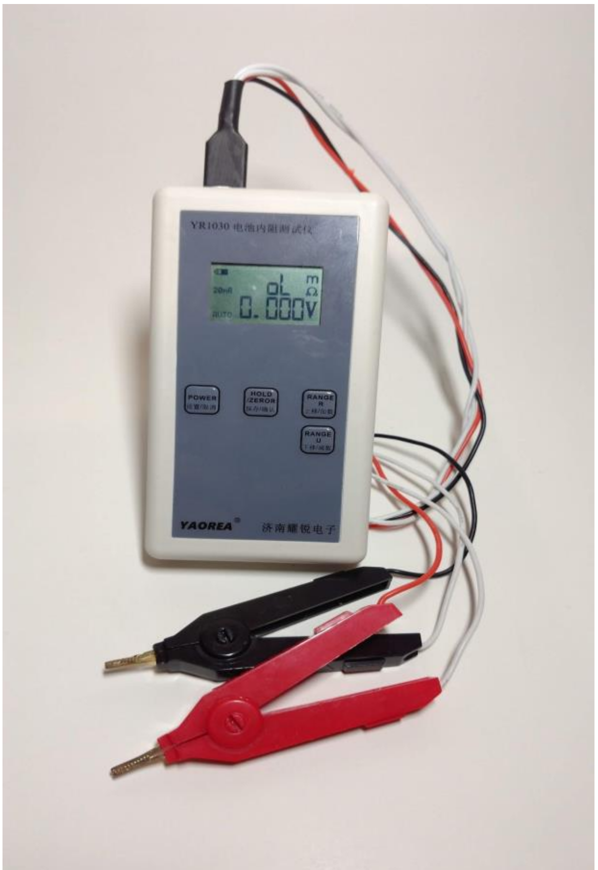


Figure 6: YR1030 Internal Resistance meter; uses AC Conductance to measure internal resistance.

Charger

The batteries are charged with a Tenergy TB6B charger. This charger will charge NiMH, lead-acid, LiFePO4 and LiPo batteries in the same unit. This eliminates the variables of using different chargers and allows the SoC of the battery to be controlled by manufacturer specifications. The balance function is used on all lithium-based batteries, so LiPo and LiFePO4, to ensure safety of the cells through constant voltage monitoring. ("Tenergy TB-6B 50w Balance Charger", n.d.)

Definitions:

Battery: a device or cell that holds energy for future use, usually characterized by an anode, cathode and electrolyte. (“BU-105: Battery Definitions”, n.d.)

BMS: Battery Management System; a charging and management system for batteries to ensure their safety and maximum charge state. (“Battery Management Systems (BMS)”, n.d.)

Rechargeable battery: A battery or battery chemistry that can be recharged and is not intended to be single use. (“BU-105: Battery Definitions”, n.d.)

Internal resistance: The resistance inside the battery, measured in ohms, that determines the thermal and discharge characteristics of the battery. (“BU-105: Battery Definitions”, n.d.)

LiPO: Lithium Polymer battery; a lithium-based battery used for high-discharge and power applications. Has an electrolyte suspended in a polymer, and is characterized by a flexible pouch. Common applications include drones and high-performance remote-control vehicles. (Is Lithium-Ion the Ideal Battery?”, n.d.)

Li-Ion: Lithium Ion battery; A lithium-based battery, characterized by a solid construction. One of the most common forms of lithium battery, as it encompasses all forms from laptop batteries to tiny rechargeables. (Is Lithium-Ion the Ideal Battery?”, n.d.)

LiFePO4: Lithium-iron-phosphate battery; a lithium-based battery with an altered anode chemistry to increase safety. Unfortunately, it suffers from a lower cell voltage (3.2v reduced from a typical 3.7v Li-Ion cell). (“BU-107: Comparison Table of Secondary Batteries”, n.d.)

Ni-Cd: Nickel-cadmium battery; Old battery technology previously used for medium-output applications. Was phased out due to being affected by the “memory effect” (“BU-107:

Comparison Table of Secondary Batteries”, n.d.), as well as containing toxic Cadmium (CDC, 2008)

Ni-Mh: Nickel-metal hydride battery; A current battery technology used for medium discharge applications. Replaces the old Ni-Cd battery chemistry. Is unfortunately susceptible to fast self-discharge. Common applications include toys and low-cost electronics. (“BU-107: Comparison Table of Secondary Batteries”, n.d.)

Lead-acid battery: a very old battery chemistry characterized by lead plates stacked and submerged in sulfuric acid to hold charge. Very low power-to-weight characteristics but features a high discharge rate and very stable chemistry. Common applications include car batteries. Will be abbreviated “Pb”. (“BU-107: Comparison Table of Secondary Batteries”, n.d.)

Results:

Chemistry	Avg. Pack Internal Resistance	Energy Density	Avg. 5A Load Result	Avg. 10A Load Result	Measured Capacity @ 10A	Avg. Time to 8v @ 10A
Pb	38.4 mΩ	79.84 Wh/L	19:59	7:14	1166mAh	7:14
NiMH	67.25 mΩ	159.29 Wh/L	35:20	16:56	2833mAh	16:56
LiFePO4	74.75 mΩ	184.50 Wh/L	36:32	18:13	3000mAh	**Not reached**
LiPo	**8.575 mΩ**	**456.14 Wh/L**	35:48	17:59	3000mAh	**Not Reached**

Figure 7: Chart with measured values per each battery chemistry; bolded are the most favorable values.

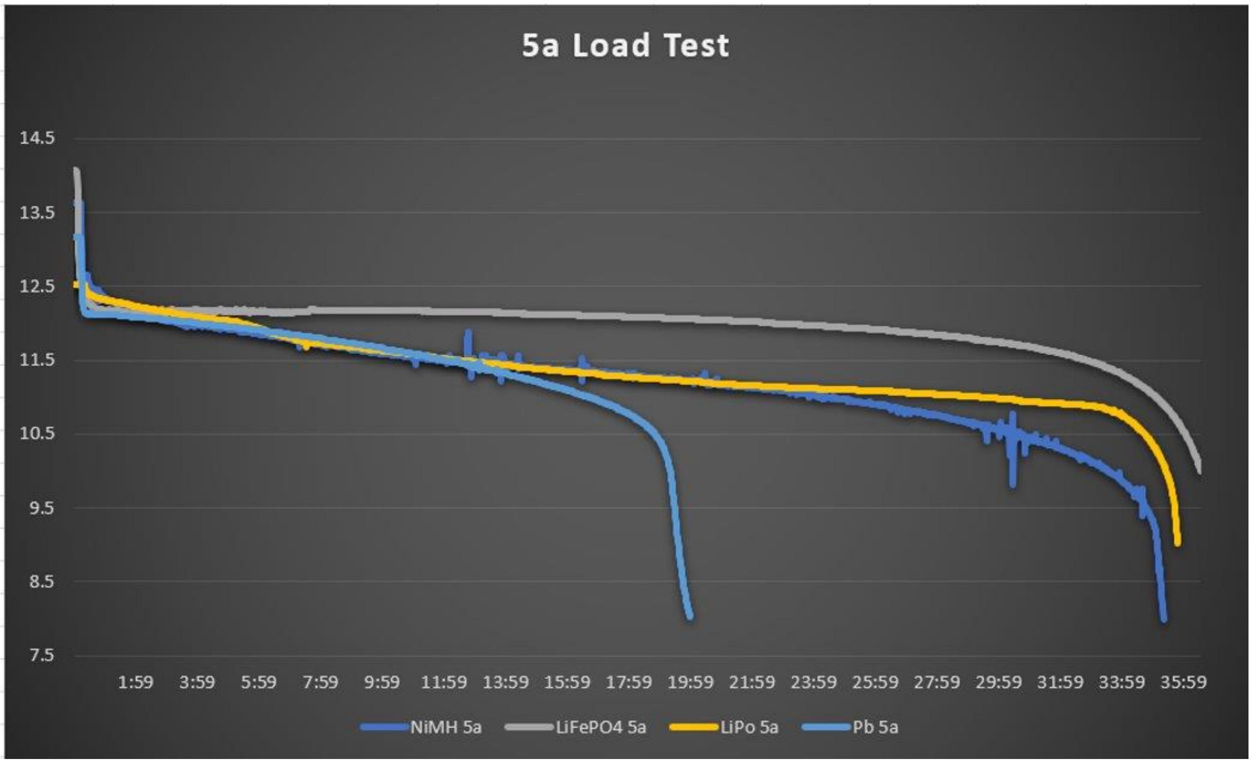


Figure 8: A graph of discharge curves at a current of 5 amps.

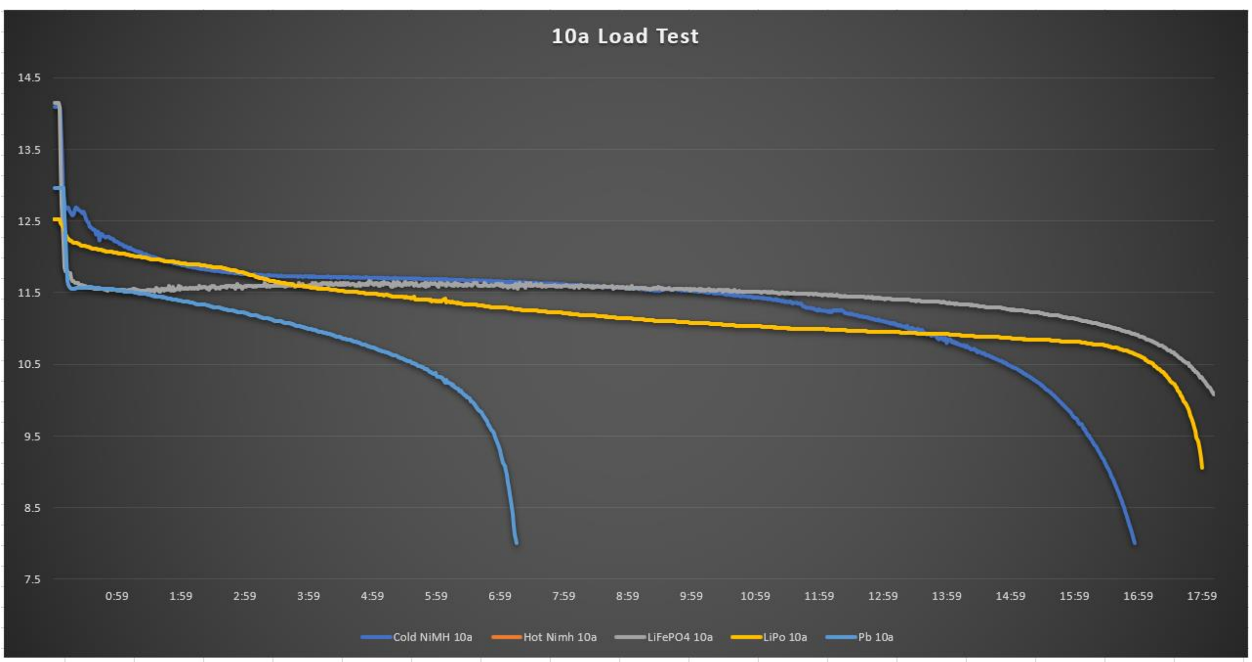


Figure 9: A graph of discharge curves at a current of 10 amps

From figures 8 & 9, we can draw a few conclusions as well as verify the results. All the battery chemistries held a relatively constant voltage from the start of the test until 2:30, which is approximately the length of an FTC match. Meaning, if there were to somehow have a motor stalled on a robot from the beginning of the game to the end of the game, any of these battery chemistries would endure okay. However, immediate run performance aside, NiMH, LiPo, and LiFePO4 had a relatively consistent discharge curve over the course of the testing, where the lead-acid battery voltage tapered off slower but earlier than the other lithium chemistry batteries.

We can verify the data from the tester through a few simple methods. Battery capacity is rated in mAh or Ah (milliamp-hours or amp-hours), where 1 Ah = 1000 mAh ("BU-503: How to Calculate Battery Runtime", n.d.). That means that for a battery rated at 3000mAh, we should be able to draw 3 amps from it for 1 hour before fully discharging. If we were to draw 10 amps from it, it would take approximately 18 minutes to fully discharge. The LiFePO4 battery lasted approximately 18 minutes at 10 amps, showing a measured capacity of 3000mAh. The LiPo battery also lasted at just under 18 minutes, which gives a measured capacity of approximately 3000mAh. The NiMH battery fully discharges at approximately 17 minutes, giving a measured capacity of approximately 2833mAh. The lead-acid battery, however, at just over 7 minutes of runtime, gives a measured capacity of approximately 1166mAh.

There are two rather strange phenomenon that are shown in the discharge curve graphs though. First, the LiFePO4 battery voltage actually increased as the testing elapsed, which was not characteristic of any of the other battery chemistries. The second is the abysmally low measured capacity of the lead-acid battery.

What was discovered was during testing, the cells of the LiFePO4 battery heated themselves up to a warm temperature of about 40 degrees C. It is known that increasing the temperature of lithium battery will increase both the discharge rate and voltage of the cell by increasing the chemical reaction rate of the battery, so this upwards curve could be caused by this phenomenon. (Nur Hazima Faezaa Ismail et al, 2013)

Peukert's Law

What was also discovered during testing is that all the lead-acid batteries fell significantly short of their rated capacity. For a battery rated at 3400mAh, drawing a 10 amp load from it should net a runtime of (3.4Ah/10A) = 0.34 hr, or 20.4 minutes. However, the batteries reached the 8v cutoff limit after only approximately 7-8 minutes of runtime, so in the worst-case scenario, these batteries tested in at ((7 min/60 min) * 10A) = 1.166Ah = 1166mAh. While the batteries were rated for approximately 3400mAh, they were only testing up to, at most, 1350mAh. The test was repeated 6 times over the two batteries tested to verify the results. Upon testing, this netted approximately 34.3% of the runtime the batteries were originally rated for.

The name for this phenomenon is Peukert's Law, where a lead acid battery will exponentially decrease its rated capacity based on how much current is being drawn from it. (Vervaet & Baert, 2002).

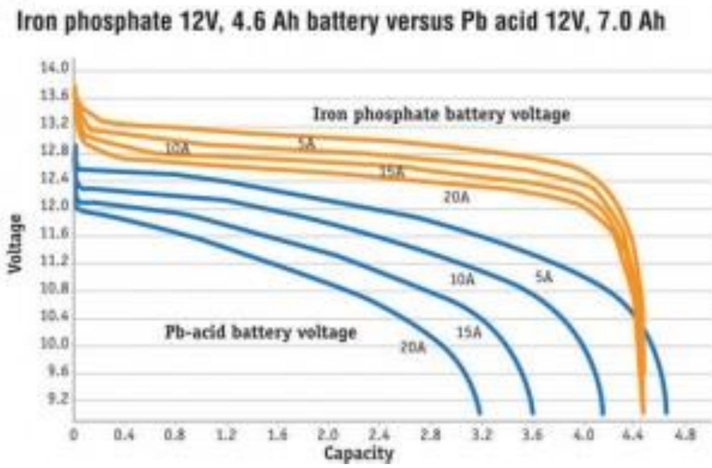
$$t = H\left(\frac{C}{IH}\right)^k$$

where:

H is the rated discharge time (in hours),
C is the rated capacity at that discharge rate (in ampere hours),
I is the actual discharge current (in amperes),
k is the Peukert constant (dimensionless),
t is the actual time to discharge the battery (in hours).

Figure 10: Peukert's Law formula (Vervaet & Baert, 2002).

Figure 11: The practical effects of Peukert's law on lead-acid batteries versus lithium-based batteries (Karrack, 2017).



A lithium or nickel-based battery will be significantly less affected by this phenomenon, as shown in Figure 11.

There is also a telltale sign of this on batteries: most commercial batteries may have a rating like 18Ah (20HR), where the battery capacity is rated based on a 20HR, extremely slow discharge.

From Reg Nicosen: “A typical Amp Hour specification might read, ‘100 AH @ 20HR’. The specification is saying that the battery will provide 100 Ah over a 20 hour period, at rate of 5 amps(100Ah/20hr = 5 amps)... Given the two facts; limited depth of discharge rating per the manufacturer (limited by designlife testing), and Peukert’s law, only ~30% of the Ah is usable. Also given the fact that 95% of a lithium batteries Ah is usable, a lithium battery that is 1/3 the Ah rating of a lead acid is actually equivalent. So a 4Ah lithium battery could be considered to be equivalent to a 12Ah lead acid, thus the justification for EqAh up to 3 times the true Ah” (Nicosen, 2015). This makes a lead-acid battery completely non-viable for FTC applications, as it would require a significantly over-rated battery to get anywhere near the same runtime as the already-standard NiMH battery.

Destructive testing evaluation

Destructively evaluating these batteries was accomplished by using two methods: short circuiting the battery and attempting to puncture the battery. The adapted EUCAR in Figure 1 will be used to assess safety ratings. Short circuiting the battery terminals all resulted in a

EUCAR rating of 1- the mandatory 20A fuse installed inline with each battery prevented cell damage or fires. All that required was a replacement of a small fuse, as well as the BMS on the LiFePO4 battery which simply shut off and required the short to be removed. There exists a risk to damage the wires and short circuit it after the inline fuse that was added for testing purposes, but if any specific battery chemistry was adopted, a battery manufacturer would be able to account for this risk by moving the fuse or BMS closer to the battery itself, removing any unnecessary risk of battery short through damage of unprotected leads. Attempting to puncture these batteries also led to interesting results. Due to the construction of the LiFePO4 and NiMH batteries using round cylinder shaped cells with a steel casing, it was impossible for a nail to puncture into the sides of these cells, resulting with a nail that was captured by the construction of the battery while having no loss in performance or danger to the user. The same would probably be seen with a Li-Ion battery in the same cylindrical format, as it is very hard to damage the individual cells of the battery physically.

The lead-acid and LiPo batteries both, however, suffered physical damage from these attempts. The lead-acid battery had the nail stuck inside its plastic casing, without any apparent short-circuiting or reaction inside the battery. Once removed, no electrolyte came out of the battery. The possibility for physical damage with such a thick plastic shell is extremely low for these lead-acid batteries. However, the LiPo battery is extremely vulnerable to physical damage due to its unprotected pouch format, with only a thin layer of plastic wrap surrounding the battery, compared to a thick plastic shell or a steel casing. The LiPo battery swells up extremely violently when punctured with a nail and will cause significant battery damage. Shown in Figure

12, the battery did end up rupturing its plastic casing and catching on fire, so the battery is given a rating of 6, the most dangerous battery so far tested.

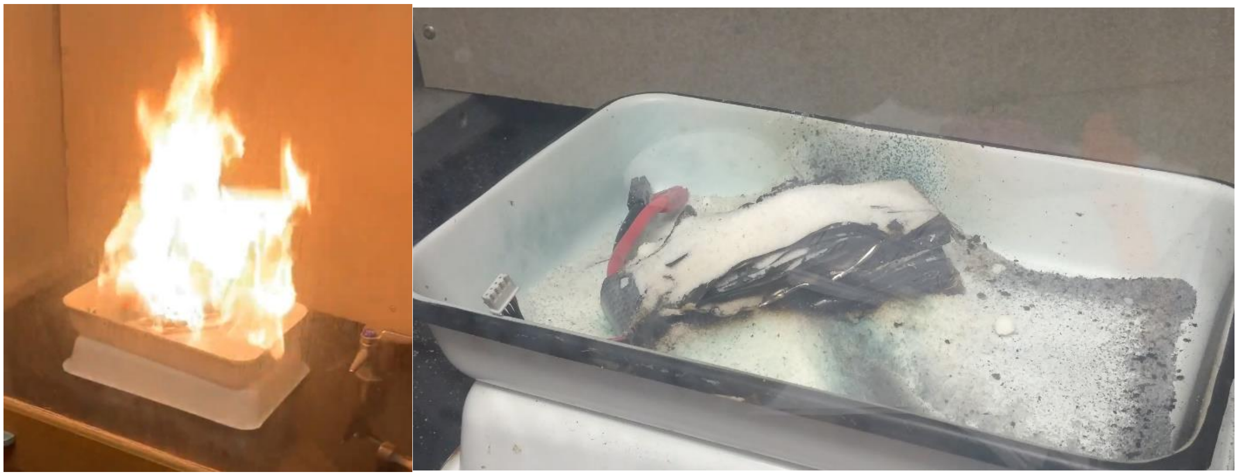


Figure 12: Lithium Polymer battery during and after nail-intrusion test.

EUCAR Ratings	Lead-acid	NiMH	LiFePO4	LiPO
Short Circuit	1	1	1	1
Puncture Test	0	0	0	6

Figure 13: Evaluted safety ratings for each battery.

Conclusion

While no immediate recommendation can be made about the perfect battery for robotics applications, there are problems to account for that remove two of the four batteries from being considered. First, Peukert's Law applying to lead-acid batteries makes them a performance and capacity downgrade compared to the already legal NiMH batteries. In addition, since they are already bulkier and significantly heavier than the NiMH battery tested, a battery comparable to the already legal NiMH battery would be almost impossible to fit on most robots and would be heavy enough to cause possible problems in robot fabrication.

Second, for Lithium Polymer batteries, they are simply not safe enough to be used in this application either. Their pouch format leaves them very susceptible to puncture and physical ingress, and the battery cells themselves are extremely unstable when it comes to overcharge, overdischarge, and short circuit conditions, due to their very chemically reactive properties (Doughty & Roth, 2012). Even mainstream commercial products with significant thought put into safety, many stories come out regarding lithium, and especially lithium polymer, battery fires. Putting them on robots with relatively exposed battery mounts and electronics is just too high of a risk. The only way to properly safeguard a LiPo battery would be building a solid casing to physically protect the battery, including a mandatory fuse for short circuit protection, an over/undervoltage protection module, and mandating the use of a balance charger. A LiFePO4 battery can get around these problems due to its already cylindrical metal construction, which is hard to physically damage, as well as the ability to use a readily available BMS with integrated safety and charging circuits and is generally less volatile battery compound. A Li-Ion battery will also be able to take advantage of these safety features but is by nature more volatile due to the chemistry of the battery (Peter & Orendorff, 2012), and would be hard to recommend when safety is a key priority.

From the four explored chemistries in this testing, two immediate choices become clear. Between NiMH and LiFePO4 batteries, it comes down to a few factors. LiFePO4 batteries have a significantly lower self-discharge rate than NiMH batteries; a NiMH battery can be significantly discharged just by sitting out and not constantly trickle charging. LiFePO4 batteries also can be charged at a much faster rate- the NiMH battery is recommended to be charged at 0.3C (0.9A), whereas the LiFePO4 battery can be charged up to 1C (3.2A), more than three times faster. LiFePO4 batteries have inherently better lifespans with a much higher charge/discharge cycle count of about 2000 cycles versus 500 for NiMH ("BU-107: Comparison Table of Secondary Batteries", n.d.; see fig. 3). Finally, the $LiFePO_4$ battery is much more energy and power dense compared to a NiMH battery, especially in what would be the final shape of a manufactured battery (see fig. 7). However, final cost may be higher for lithium-based batteries, even when factoring the relatively low cell count compared to NiMH (3-4 cells vs. 10 cells), as well as the addition of a BMS. While maybe not replacing NiMH batteries outright, $LiFePO_4$ and other lithium-based batteries serve to be worthy replacements to the decades old chemistries used in many applications.

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