Effective Battery Energy Capacity as a Function of Temperature and Discharge Current

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Abstract

The goal of this project is to analyze the effects of variable environmental temperatures and discharge currents on the effective energy capacity of common batteries. AAA batteries with different chemical compositions were considered including: alkaline, nickel-metal hydride, primary lithium, and lithium ion. Additionally, lithium coin cell batteries were tested to compare the results of different form factors. In theory, the chemical reactions and electrical processes within the batteries are optimized to perform at specific temperatures and current draws. These specifications are commonly provided by the manufacturer and give information on the "ideal" conditions for use. Operating outside of these optimal specifications could demonstrate a noticeable effect on battery life expectancy, and more specifically, lower the effective energy capacity. This project's approach to measure these effects consisted of collecting information on battery voltages under specific temperatures and discharge currents. The results demonstrated that battery behavior is altered by these conditions.

I Introduction

Nearly all common electronics rely on battery power in order to run and the lifespan of these devices often seems strongly correlated with the temperature around them. For example, a phone battery may appear to drain much quicker during the winter or in colder environments and electric cars seem to lose a noticeable amount of range after being left out in the cold overnight. To combat this, Tesla car batteries will even drain some of their energy in order to heat themselves preventing damage to the energy cells. On the other side of the temperature spectrum, electrical resistance increases with heat, so warm batteries will inherently have higher internal resistances. These observations point to the possibility that temperature extremes may have apparent effects on the effective energy capacity of batteries. Furthermore, the amplitude of the discharge current may also have an impact on battery performance. This project aims to provide objective data and conclusions on battery voltages in various environments as they are exposed to variable temperatures and drained in circuits consisting of different resistances to control the discharge current.

Batteries consist of one or more electrochemical cells that can be attached externally to power electronics in a circuit. Once connected to a circuit, a chemical reaction within the electrochemical cells converts the high energy reactants to lower energy products. The excess charge flows through the circuit providing an electric current. “There are three main components of a battery: two terminals made of different chemicals (typically metals), the anode and the cathode; and the electrolyte, which separates these terminals. The electrolyte is a chemical medium that allows the flow of electrical charge between the cathode and anode” (Bates). While powering a circuit, the anode releases electrons to the negative terminal of the battery which are then accepted by the cathode through the positive terminal. Some types of batteries can only be used once (and are referred to as “primary”) because they produce electricity until the chemical potential is the same on both electrodes. Other batteries can be recharged and reused (called “secondary”) because the internal chemical reactions are reversible by applying an external voltage in the reverse direction restoring the battery’s charge. Multiple chemicals can be used to produce an electrochemical battery cell and this lab examined four common AAA battery chemistries: alkaline, nickel-metal hydride, lithium primary, and lithium ion; as well as a lithium coin cell battery.

Battery chemistry may also provide some insights into how different chemical compositions are affected by different temperature and environmental conditions. Many important characteristics of each battery such as energy density, voltage, operating temperature range, and other factors can vary based on chemical composition. Therefore, it is expected that not all batteries will perform identically under the same conditions. Each battery type will be discussed separately to analyze how effective energy capacity is impacted for individual types. Figure 1 shows the different AAA batteries that will be evaluated. The AAA alkaline and lithium primary batteries are non-rechargeable primary batteries, whereas the nickel-metal hydride and lithium ion batteries are rechargeable secondary batteries.

Figure 1: The batteries listed from left to right: 1.5V alkaline AAA, 1.5V lithium AAA, 1.2V nickel-metal hydride, 1.5V AAA lithium ion. Each will be tested under the variable conditions (discharge current & temperature)

A few vocabulary terms in this paper need to be defined moving forward. A battery’s *open circuit voltage* is “the voltage between the battery terminals with no load applied.” It’s *nominal voltage* is “the reported or reference voltage of the battery, also sometimes thought of as the “normal” voltage of the battery” and is the voltage measured under a normal resistive load. The *cutoff voltage* is “the minimum allowable voltage. It is this voltage that generally defines the “empty” state of the battery” (MIT). We are defining the cutoff voltage to be 0.8V for our measurements. The *operating range* is the range of temperatures in which the battery is rated to function properly. Below we will discuss the manufacturer's specifications for each battery type and the expected behaviors.

Alkaline

According to the manufacturer, the AAA alkaline batteries we tested have an open circuit voltage of 1.6V and a nominal voltage of 1.45V. The batteries have an operating range of -18℃ to 55℃, but are recommended to discharge at 20±2℃. Under the optimal temperature conditions and with a 10Ω load, the battery is expected to reach its cutoff voltage defined at 0.9V in 480 minutes. Figure 2 shows the manufacturer's schematic diagram of discharge under these conditions.

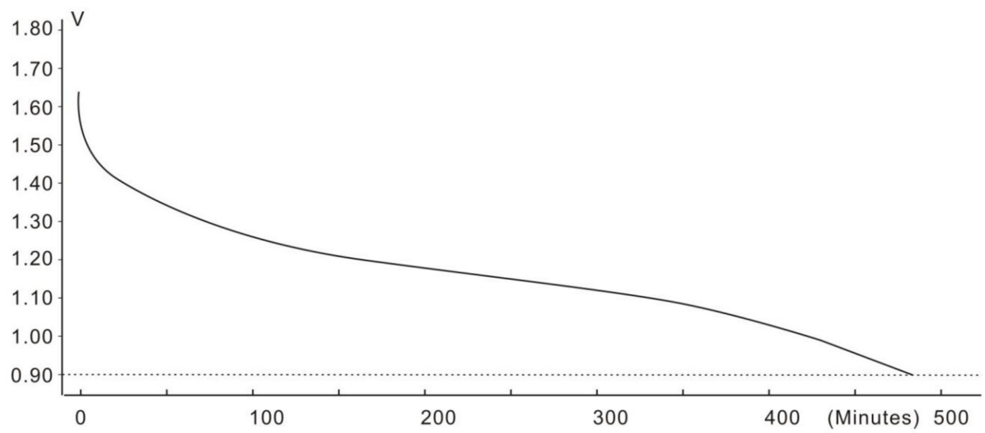

Figure 2: PKCELL Schematic Diagram of Discharge for a AAA Alkaline battery under 10Ω load at 20±2℃

Lithium Primary

The chemical composition of the AAA lithium primary batteries we are testing is specifically Lithium/Iron Disulfide (Li/FeS_2). This is just one possible composition of a primary lithium battery. This battery has an open circuit voltage of 1.8V and a nominal voltage of 1.5V but is rated to discharge at a maximum 1.5A current. The operating range is -40℃ to 60℃ and the rated cutoff voltage is 0.8V. However, figure 3 shows the rated effects that the temperatures in the operating range have on the capacity of the battery.

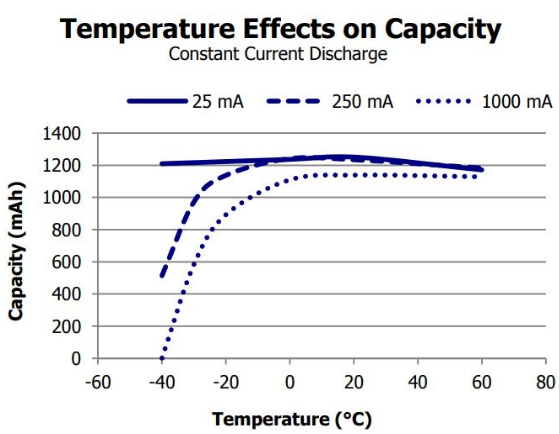

Figure 3: Energizer rating on AAA Lithium Primary battery capacity versus temperature in operating range

Nickel-Metal Hydride (NiMH)

The AAA NiMH rechargeable battery has nominal voltage of 1.2V and an operating range of 0℃ to 50℃. Figure 4 shows the manufacturer's ratings for the battery's performance at 21℃ under multiple loads.

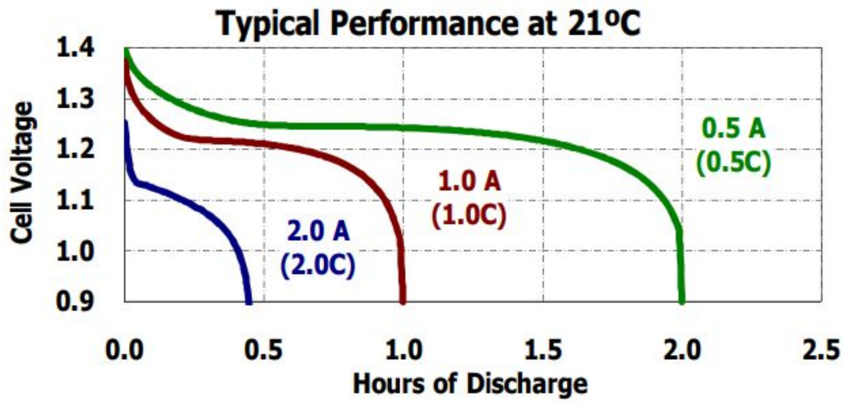

Figure 4: Energizer typical discharge characteristics of NiMH battery at 21℃ and discharge currents at 0.5A, 1.0A, and 2.0A.

Lithium Ion

The manufacturer rating of the AAA lithium ion rechargeable battery states that the nominal voltage is 1.5V and can maintain up to a 2A discharge current. However, the nominal voltage of a standard lithium ion battery is 3.0V. In order to achieve the lower nominal voltage, the AAA battery contains internal circuitry which regulates the voltage between the terminals. A lithium ion battery has an operating range of -30℃ to 60℃, however the manufacturer does not specify if the additional circuitry has any effect on this operating range.

Lithium Coin Cell

The chemical composition of the lithium coin cell battery is Lithium/Manganese Dioxide (Li/MnO_2) and has the standard nominal voltage of a secondary lithium battery of 3V and operating range of -30℃ to 60℃. However, the coin cell battery is limited to a discharge current of 390μA and has a high cutoff voltage at 1.6V. Figure 5 shows the manufacturer's ratings of voltage versus capacity at different discharge currents.

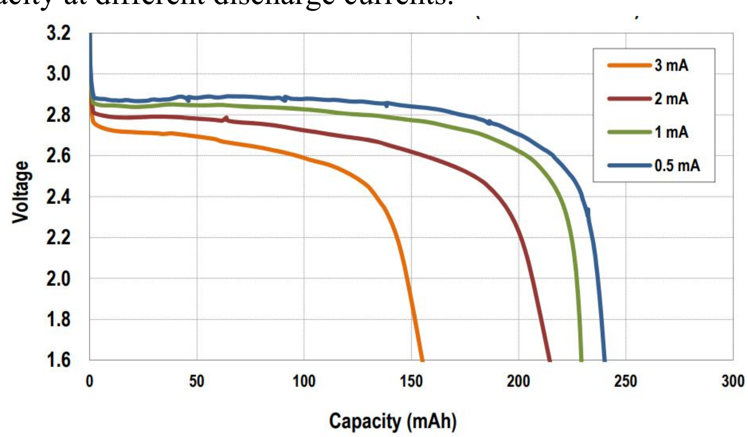

Figure 5: Energizer lithium coin cell battery discharge current voltages versus capacity

Table 1 shows the open circuit voltage that we measured for each battery type by measuring the voltage across a new battery without any load at room temperature. The measured values for both of the primary batteries matched perfectly with the manufacturer's ratings of them. Table 2 below shows the manufacturer's ratings for the nominal voltage, capacity, and typical discharge current for each type of battery.

	Battery Type	**Measured Open Circuit Voltage (V)**
Primary AAA	Alkaline	1.6
Primary AAA	Lithium Primary	1.8
Secondary AAA	Nickel-Metal Hydride	1.3
Secondary AAA	Lithium Ion	1.5
Secondary Coin Cell	Lithium	3.2

Table 1: Measured open circuit voltages of each battery type at room temperature

	Battery Type	**Nominal Voltage (V)**	**Capacity (mAh)**	**Typical Discharge Current (mA)**
Primary AAA	Alkaline	1.45	1000	10
Primary AAA	Lithium Primary	1.5	1250	10
Secondary AAA	Nickel-Metal Hydride	1.2	1000	200
Secondary AAA	Lithium Ion	1.5	500	Up to 2000
Secondary Coin Cell	Lithium	3.0	220	0.2

Table 2: Information on voltage, capacity, and typical drain information provided by manufacturers for batteries

II Methods

This project consisted of the use of an ATmega2560 microcontroller chip on an Arduino Mega 2560 board. This board is interfaced with a collection of sensors relevant to data collection and additional electronics (more detail can be found under ‘Sensors’ later in this section). All of these elements are connected on a PCB as shown in Fig. 2b. In total, the main part of our (DAQ) device includes temperature sensors for reporting ambient/object temperature, LCD display to show relevant information, 5-count AA battery pack used to power the device, microSD board for data collection/storage, on/off button, current/voltage sensor and ribbon cable connectors (used for connecting protoboards. The electronics were later placed in a 3D printed case which can be seen in Fig. 6a.

Our project needed to accommodate a broad range of ambient temperatures for our tested batteries so therefore we created a set of protoboards which would house our batteries and various temperature sensors. Those protoboards were connected back to our circuit boards with ribbon cables.This allowed us to place our batteries at a distance in environments that would not besafe for the rest of the electronics involved in the project. These can be seen in Fig. 7.

Figure 6a: Main DAQ Instrument (with 3D printed cover)

Figure 6b: Main DAQ Instrument (picture left: LCD display, microSD, 4x3 keypad, on/off button, ribbon cable connectors) (pictured right 5 AA battery power supply, arduino board, INA219 voltage/current sensor)

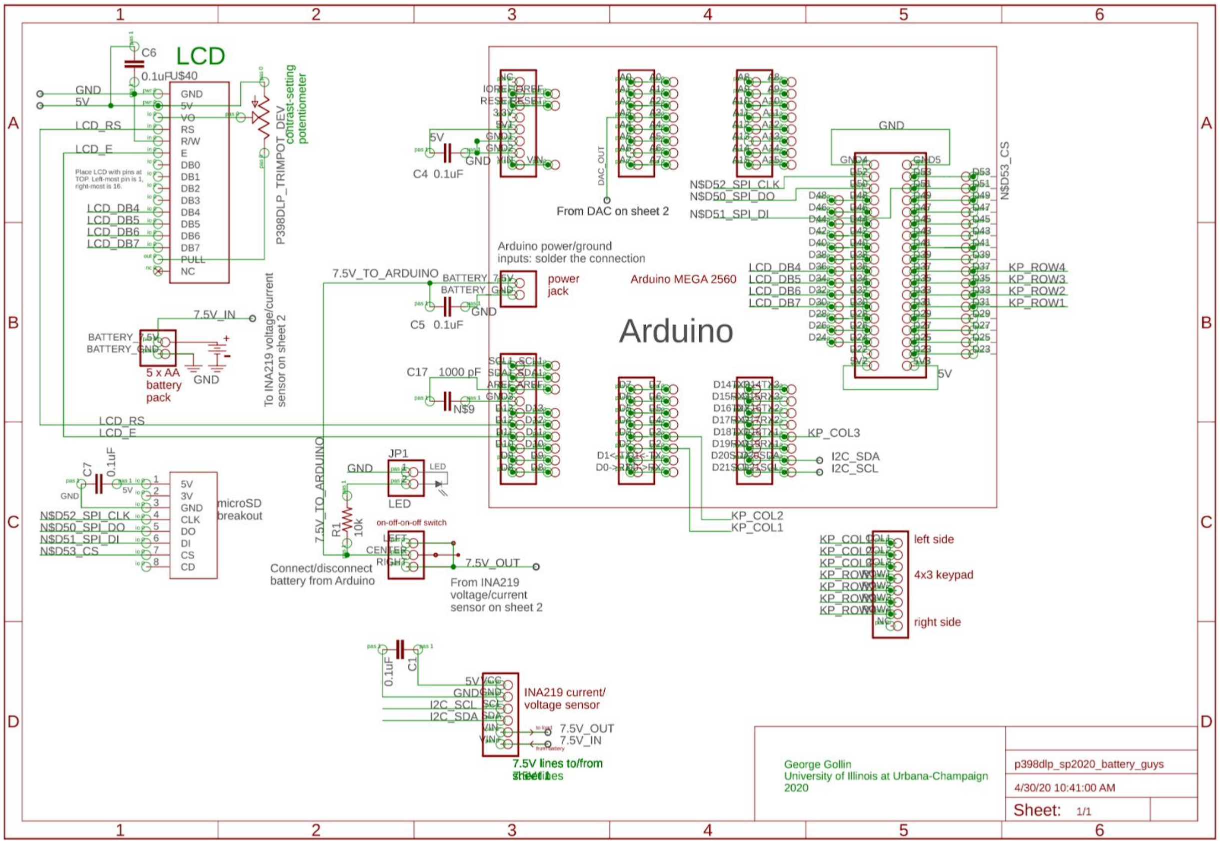

Figure 6c: The schematic for our primary DAQ device. Provides technical details for the electronics involved in the experiment

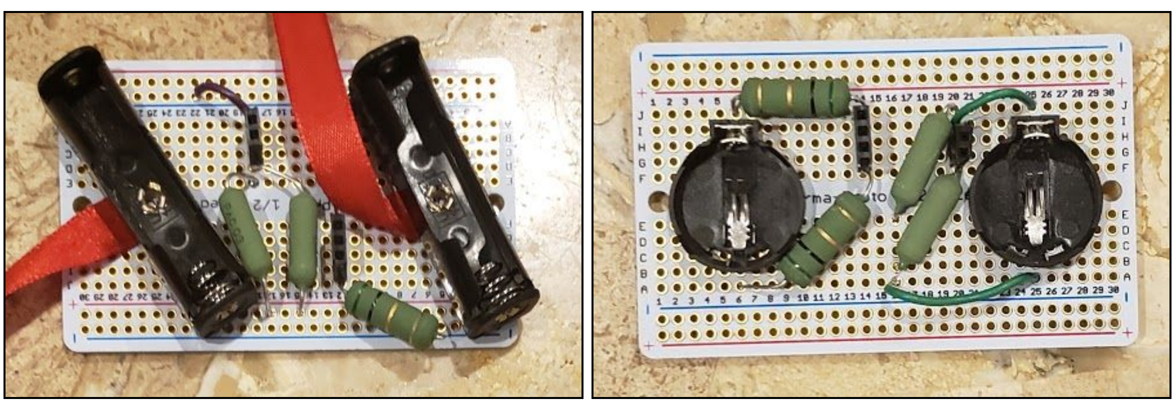

Figure 7a: Protoboards holding the casing for AAA and coin cell batteries

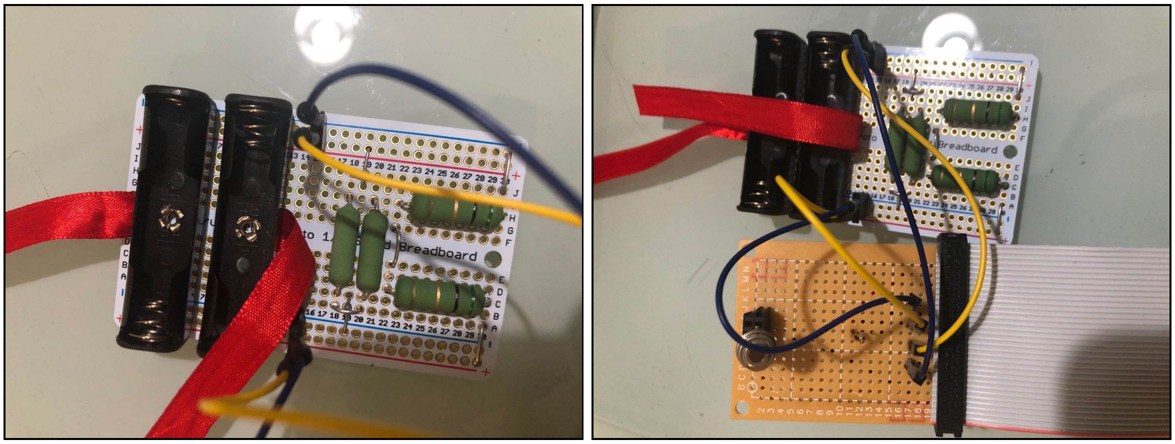

Figure 7b: Left: Connection between the Protoboard and the sensor board through 4 wires;
Right: Connection between the sensor board and the Daq instrument through 2 ribbon cables.

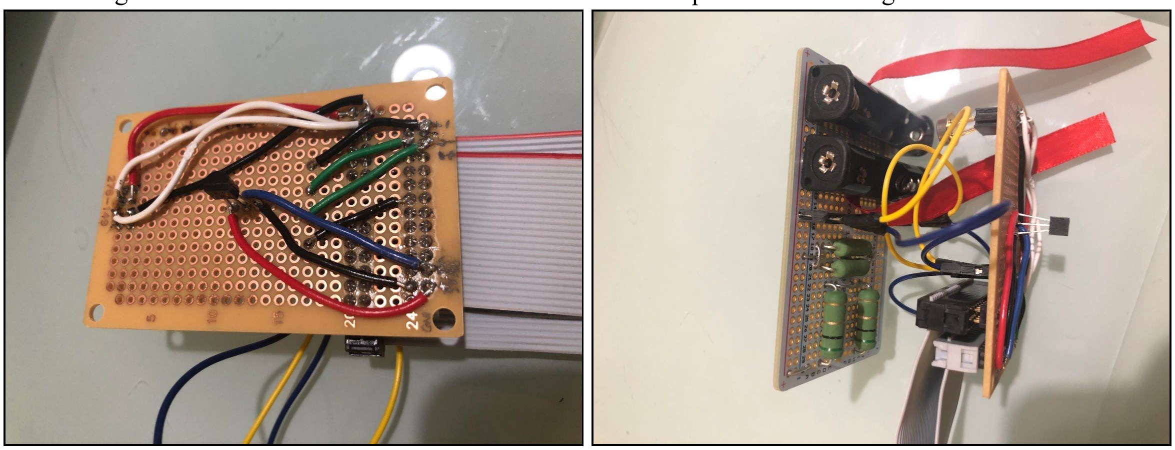

Figure 7c: Left: TMP sensor at the bottom side of sensor board;
Right: Working position of the two boards (photoed for clarity without the case).
One may note that the IR sensor on the right side is not exactly pointed at the battery casing. However, during data acquisition, the position of the IR sensor is aligned directly in front of one of the battery holders by a case holding the two boards.

Initially, the group familiarized itself with the general electrical functions of the Arduino Mega 2560 board with the use of breadboards as can be seen in Fig. 8. We were able to wire the basic layout of our instrument including the various sensors. After testing those sensors with basic arduino software to check functionality, we moved on to soldering our electronics onto a printed circuit board.

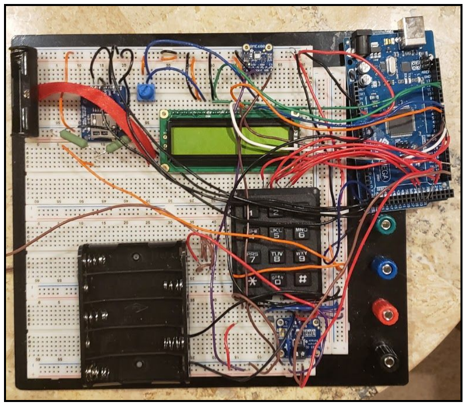

Figure 8: An example of a breadboard used as part of this project

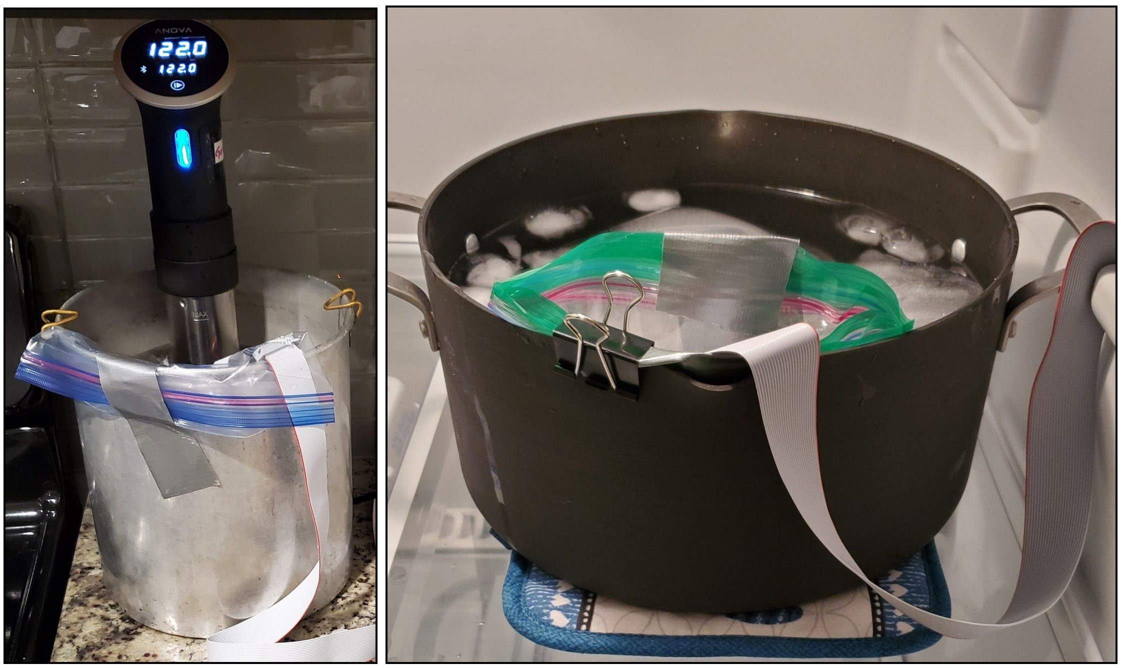

Figure 9: Measurements being taken in hot environment (left) using a sous vide to maintain constant 50°C temperature and cold environment (right) using a bath of ice water stored in the fridge to maintain constant 0°C temperature

Sensors/electronics

The sensors/electronics involved in our experiment include the following:

<u>TMP36</u>: Measuring range: −40°C to 125°C

The TMP36 is an analog signal temperature sensor, whose output voltage has a linear relationship with the temperature of the device. We can easily calculate and record the environmental temperature by reading from one analog pin. Power consumption is very small and produces minimal self heating.

MLX90614: Measuring range: −40 to 125°C (case) −70 to 380°C (object)

The MLX90614 consists of an IR sensitive thermopile, which converts thermal energy to electrical energy. It has a higher resolution than the TMP36 sensor, but it uses I2C protocol to connect with Arduino; therefore, we can only install a single MLX90614 sensor for our experiment. We use MLX90614 to monitor the temperature of the battery body by pointing it to the battery linked to 1Ω load during the experiment. It is held relatively close so that the cone of exposure to the batteries is increased to provide better accurate reading of battery temperature.

A thermopile is composed of thermocouples, which can generate a voltage proportional to temperature difference between the two ends (known as the Seebeck Effect). Seebeck discovered that a circuit made of two dissimilar metals conducts electricity if the two places where the metals connect are held at different temperatures.

INA219

A current/voltage sensor with a precision amplifier that measures the voltage across an internal resistor with 1% precision. It is mounted between the battery pack and power input of Arduino. Therefore, we can monitor the status of our battery pack conveniently.

LCD display

A basic LCD display that allows us to see whether the device is functioning correctly. Our DAQ code will output messages on the LCD screen.

4x3 keypad

A keypad of 12 different keys connecting to Arduino by digital pins. We use the keypad to control the device by opening/closing files, starting/stopping measurements, and displaying measurements of individual sensors.

MicroSD breakout board

A device for us to add external removable mass storage. It writes our experiment data into a micro SD card for convenient importation into our computers.

Sous vide

The sous vide has a built-in module to control internal temperature, we used it to provide a constant temperature for our ‘hot’ and “room temperature” environments.

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DAQ

Once the electronics and hardware were prepared, our group used data acquisition software developed by one of our group members to collect information on parameters as batteries discharged. As the code runs, information is collected once every 0.5 seconds to preserve the accuracy of energy capacity calculations, as well as limit the file size and processing time.

We used the analog pins on the Arduino to record the voltage across the two resistor loads, and across the TMP36 sensor so that we can calculate the environmental temperature. Arduino has an built-in Analog to Digital Converter (ADC), which takes in a continuous sequence of continuous values and outputs a sequence of discrete values. In our experiment, the input is real continuous battery voltage, and the output is discrete value of voltage readings. In order to improve accuracy and reduce error caused by random fluctuation, we take an average of 10 readings while outputting battery voltages to the microSD every 0.5 seconds. This measure is aimed to reduce the smallest step of our voltage measurements, and create a smooth graph while we zoom in to see the change of voltage over a short time. The effect of taking the average will be discussed in the discussion section.

Besides analog communication, we used I2C (a serial protocol usually utilized for small microprocessor communication) to connect with the MLX90614 (IR temperature sensor) and record its set of environmental temperature plus object temperature. Due to technical limitations, we could install only one IR sensor onto our printed circuit board. Therefore, we used it to measure the battery with a load of smaller resistance in order to observe the more significant effect of discharging on battery's temperature. In theory, if a battery is being discharged with a larger current, there could be a buildup of heat within it.

The data is later fed into a python code which outputs a graph of voltage over time with additional information to identify any important parameters. Those graphs were analyzed to determine if temperature and discharge current show any effect on energy capacity. The python code also includes calculations of total energy output to see which conditions allowed which batteries to output the most energy. Our method of calculating total energy outputted by AAA batteries is by summing up each $\Delta E = (V^2/R)\Delta t$ where $\Delta t = 0.5 seconds$ when $V \geq 0.8 volts$.

To measure the effects of temperature, the group utilized the use of protoboards to house batteries and temperature sensors separately from the printed circuit board. Those protoboards were later enclosed in ziploc bags and submerged in either hot or cold water to attain the desired temperature extremes.

To measure the effects of discharge current, we utilized circuits which drained batteries with two different resistive loads: 1Ω and 10Ω. This ideally should provide two currents with a difference of a factor of 10 between them.

Due to limitations provided by our experimental setup, specifically high current draws, the coin cell battery, while tested, ultimately displayed behavior that was not appropriate in addressing the goals of this project. More information can be found at the end of the 'Discussion' section in this report.

III Results

Alkaline

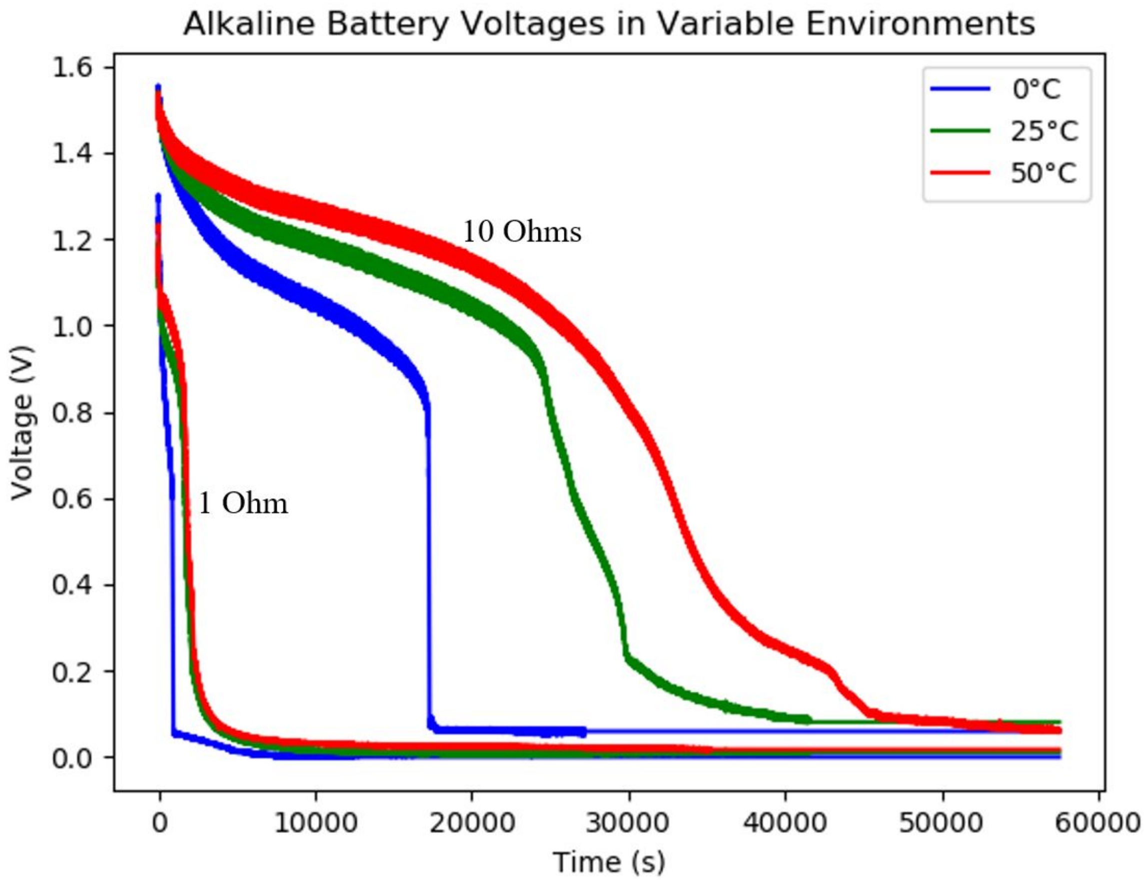

Figure 10a: AAA Alkaline battery results

Figure 10a above shows the results from the measurements taken on the AAA Alkaline batteries. It is clear from the graph that the temperature did impact the effective energy because the battery in the cold environment performed much worse than the room temperature battery while the hot temperature battery took the longest to reach the cutoff voltage. Additionally, the discharge current affected the battery performance because the initial voltage of the batteries with a 1Ω load did not reach the nominal voltage.

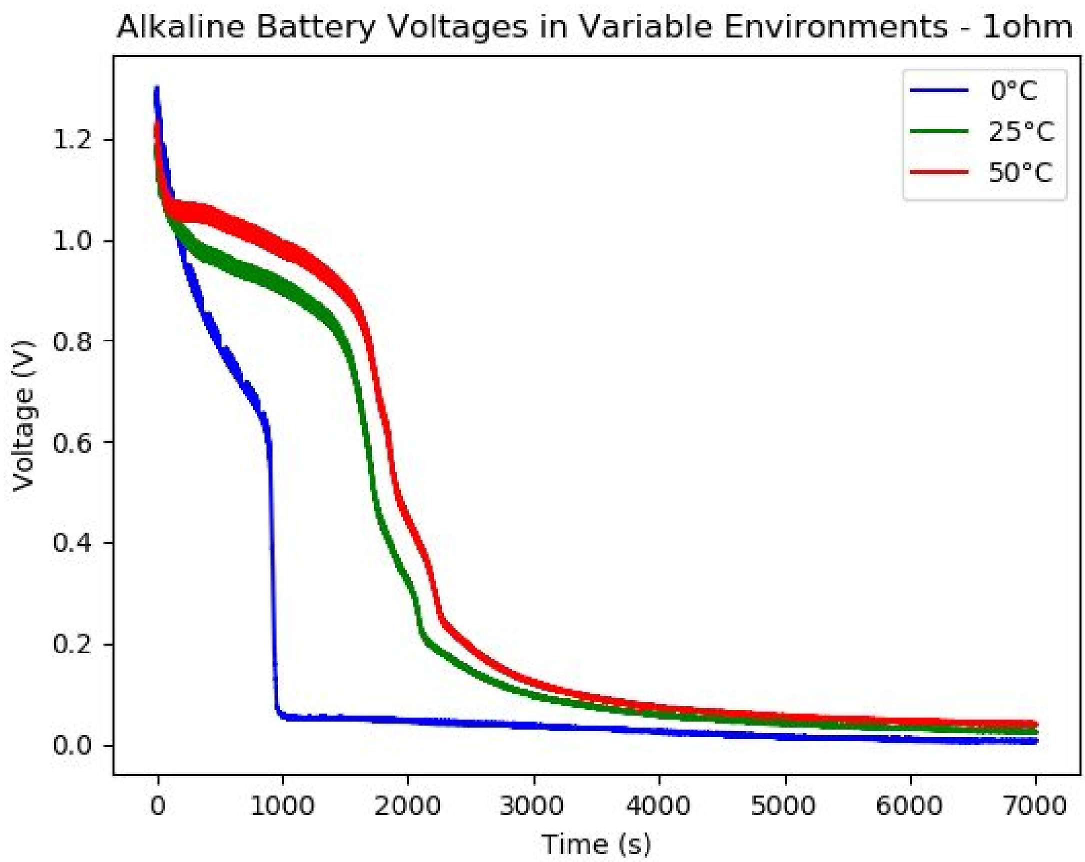

Figure 10b: AAA Alkaline battery results with 1Ω load

Figure 10b is the results of measurements of AAA Alkaline batteries zoomed in for displaying the voltage data under 1Ω load. The results are similar to those under the 10Ω load in that the 0°C battery dropped in voltage significantly faster than the other two, and the 50°C battery performed slightly better (lasted longer) than the 25°C.

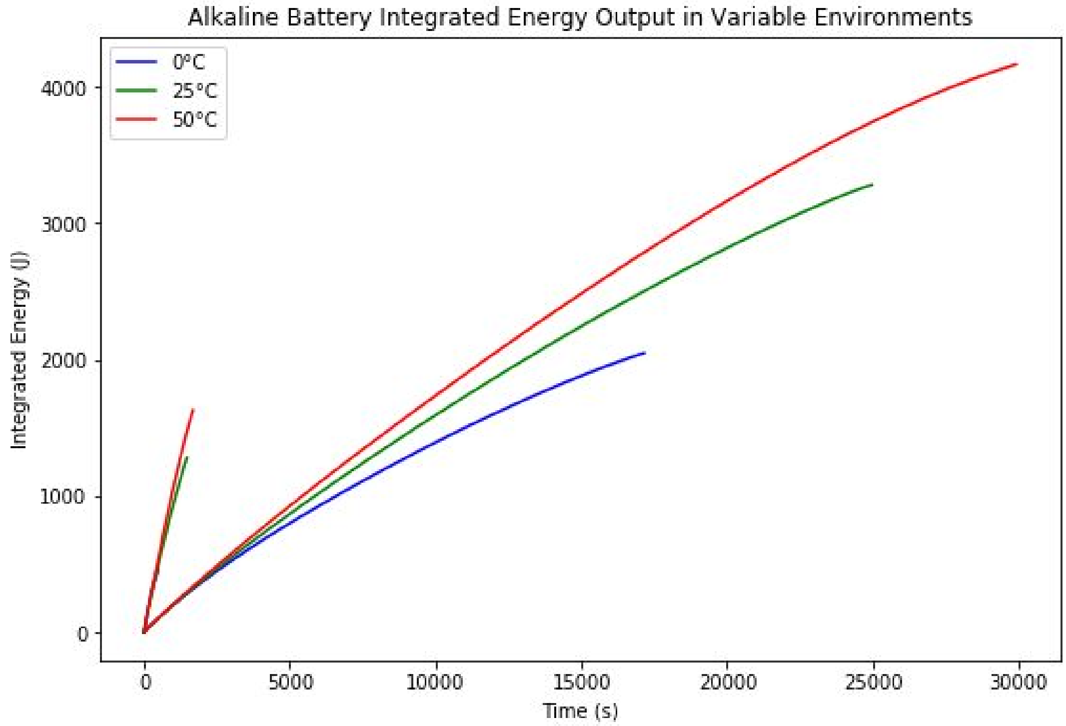

Figure 10c: The integrated energy output of AAA Alkaline battery with respect to time

Figure 10c shows the graph of total energy output from AAA Alkaline batteries of two loads and three temperature conditions. This was achieved by taking an area integral of the voltage graphs until they reached 0.8V. We can observe that the curves of 1Ω load are steeper than the curves of 10Ω load. Additionally, the peak value for the hot temperature is greater than the peak values for room temperature which is still greater than the peak values for cold temperature. This means that the effective energy is greatest in hotter environments for Alkaline batteries.

Lithium Primary

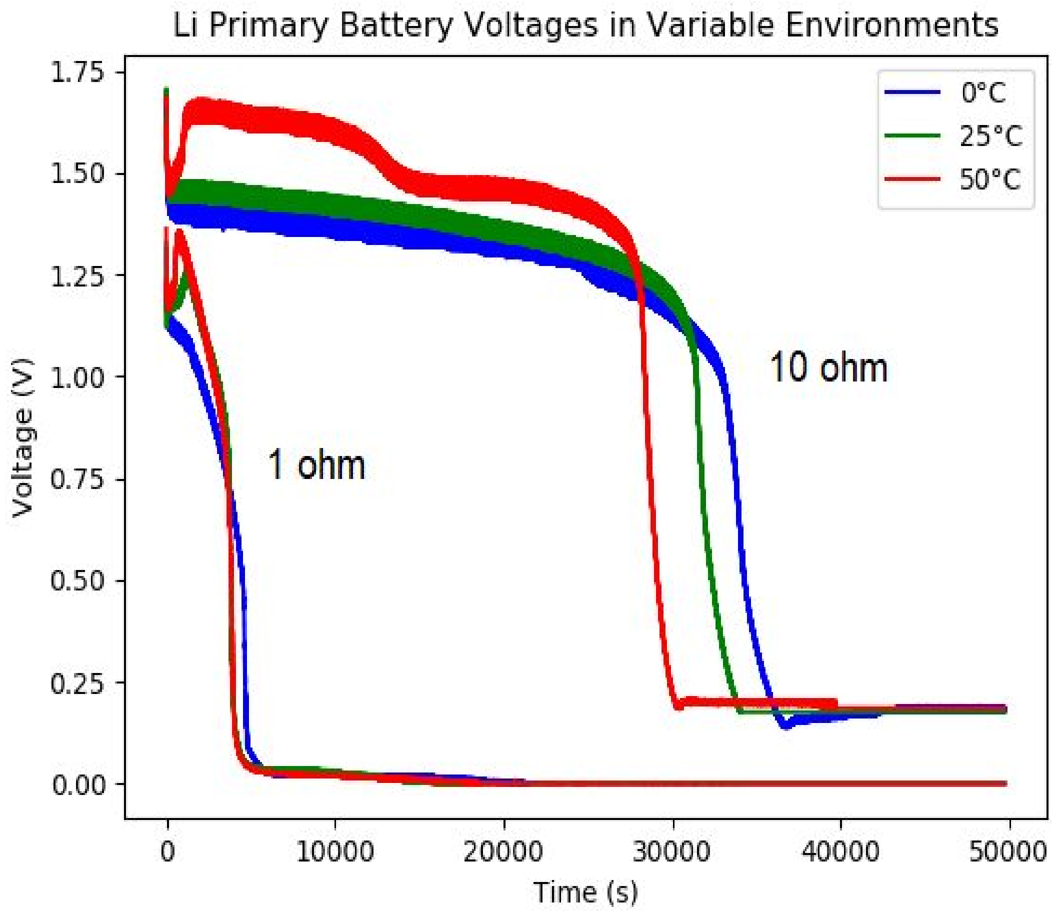

Figure 11a: AAA Lithium Primary battery results

Figure 11a above shows the results from the measurements taken on the AAA Lithium Primary batteries. This data shows that the colder temperatures performed better than the warmer ones. The hot temperature batteries under both resistive loads start with higher voltage peaks, but drop sooner, whereas the cold environment has slightly lower initial voltages but last longer. Once again, the 1Ω resistive load prevented the batteries from reaching the nominal voltage.

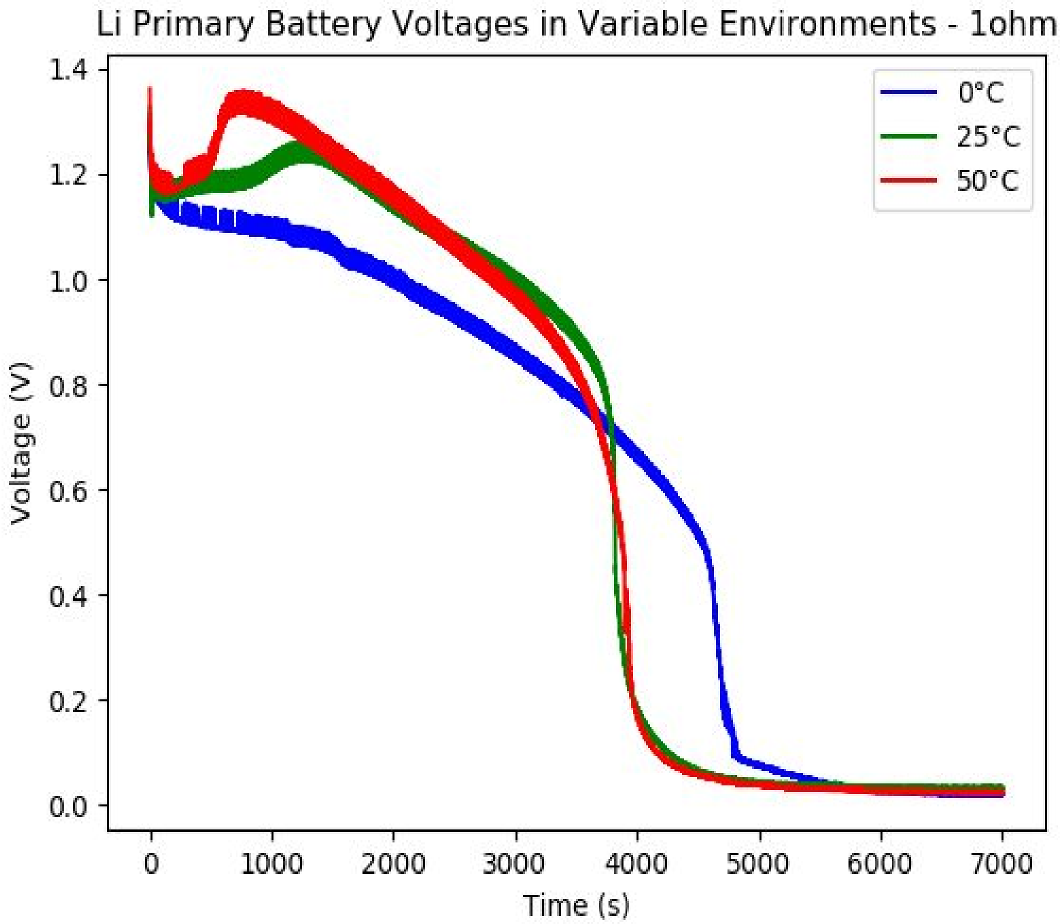

Figure 11b: AAA Lithium Primary battery results with 1Ω load

Figure 11b is the results of measurements of AAA Lithium Primary batteries zoomed in for displaying the voltage data under 1Ω load. Similar to the 10Ω load, the cold temperature lasted the longest, however, due to the steepness of the initial voltage decay, all three conditions reached the cutoff voltage at around the same time.

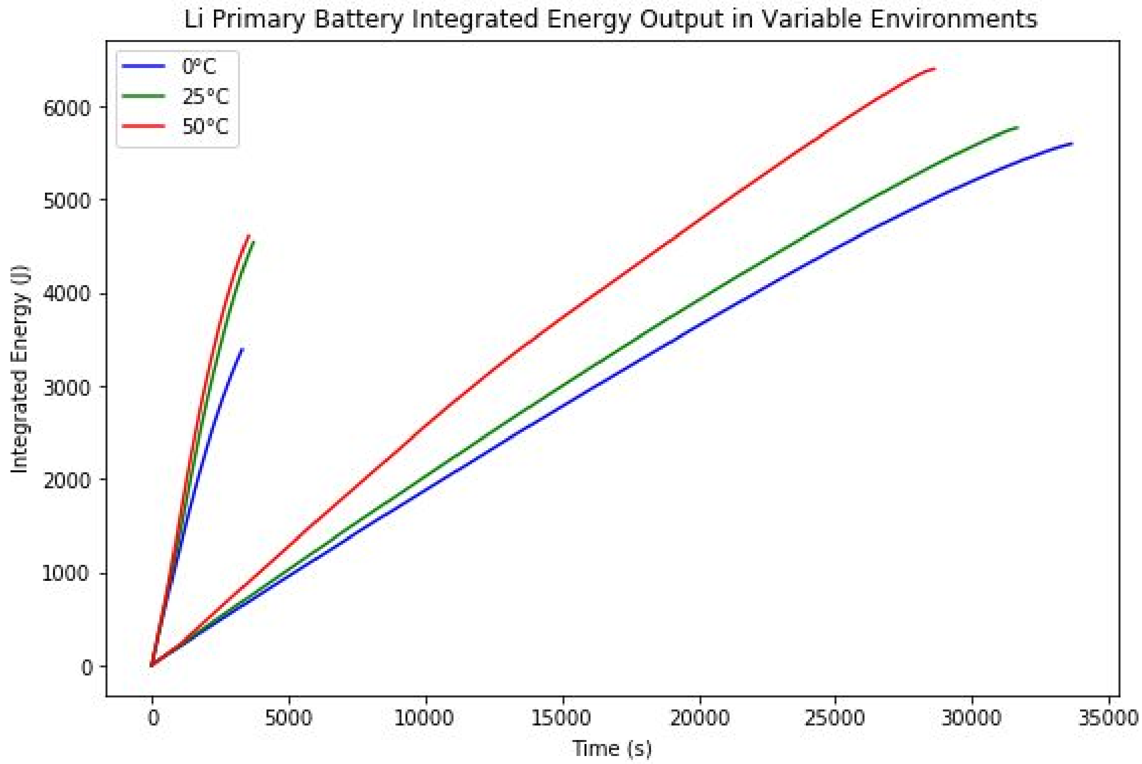

Figure 11c: The integrated energy output of AAA Lithium Primary battery with respect to time

Figure 11c shows the graph of energy output from AAA Lithium Primary batteries of two loads and three conditions. We can observe that the curves of 1Ω load are steeper than the curves of 10Ω load meaning that they give off energy at a substantially quicker rate. Despite the colder temperature lasting longer than the hotter temperature as seen in figures 10a, the hotter temperature has a higher effective energy due to the higher initial voltages.

Nickel-Metal Hydride

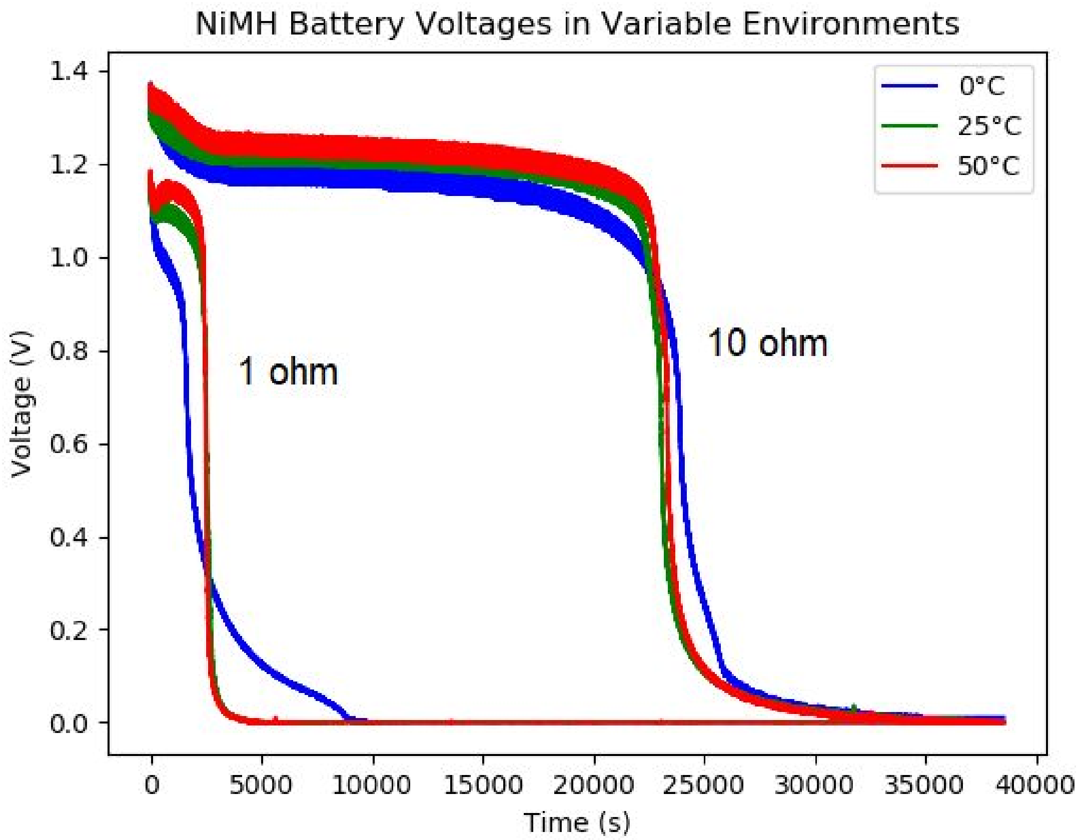

Figure 12a: AAA Nickel Metal-Hydride battery results

Figure 12a displays voltage values around 2 hours (1Ω) and 11 hours (Combined). Typical battery drain will display a steep dropoff in voltage as can be seen above. Unlike the other battery types, the NiMH batteries are barely affected by the change in temperature at 10Ω. Similar to the other batteries though, the 1Ω batteries do not quite reach the nominal voltage.

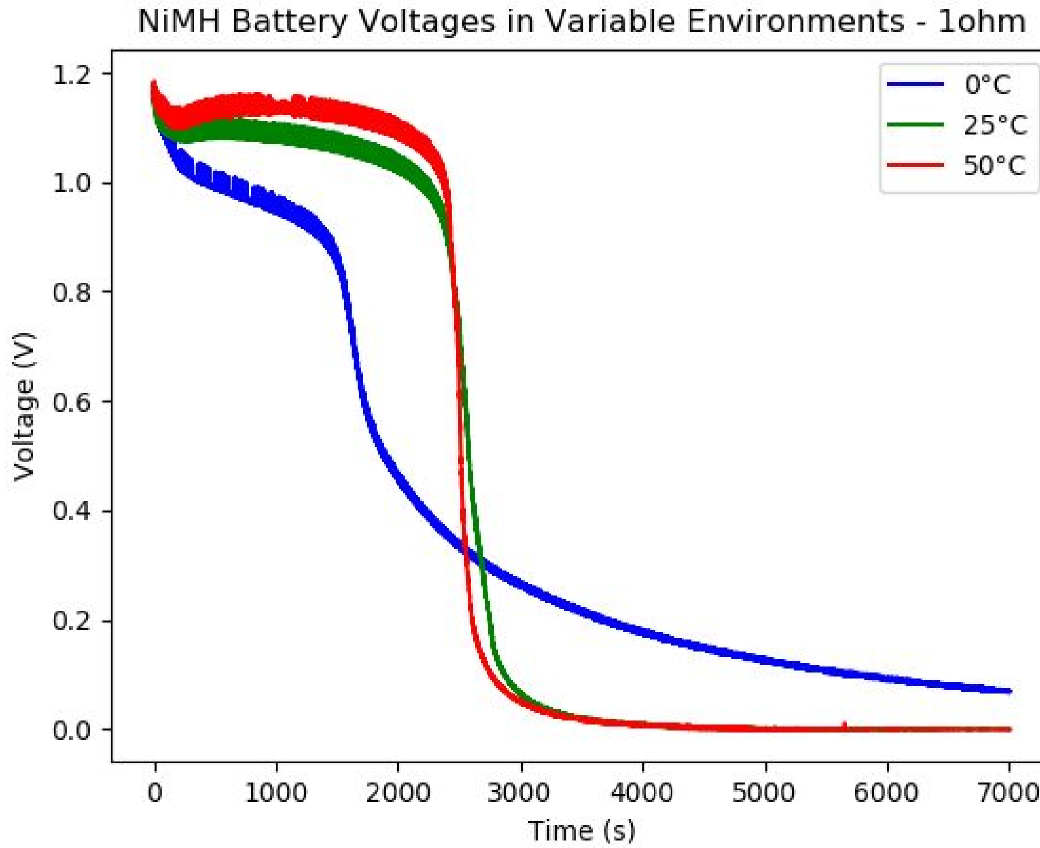

Figure 12b: AAA Nickel Metal-Hydride battery results with 1Ω load

Figure 12b is the results of measurements of AAA Nickel Metal-Hydride batteries zoomed in for displaying the voltage data under 1Ω load. Similar to the 10Ω results, the room temperature and hot temperature batteries reach the cutoff voltage at the same time, however the cold temperature with a 1Ω load does not perform well and dies quickly but has a strange voltage decay over a long period rather than a steep drop like the other conditions.

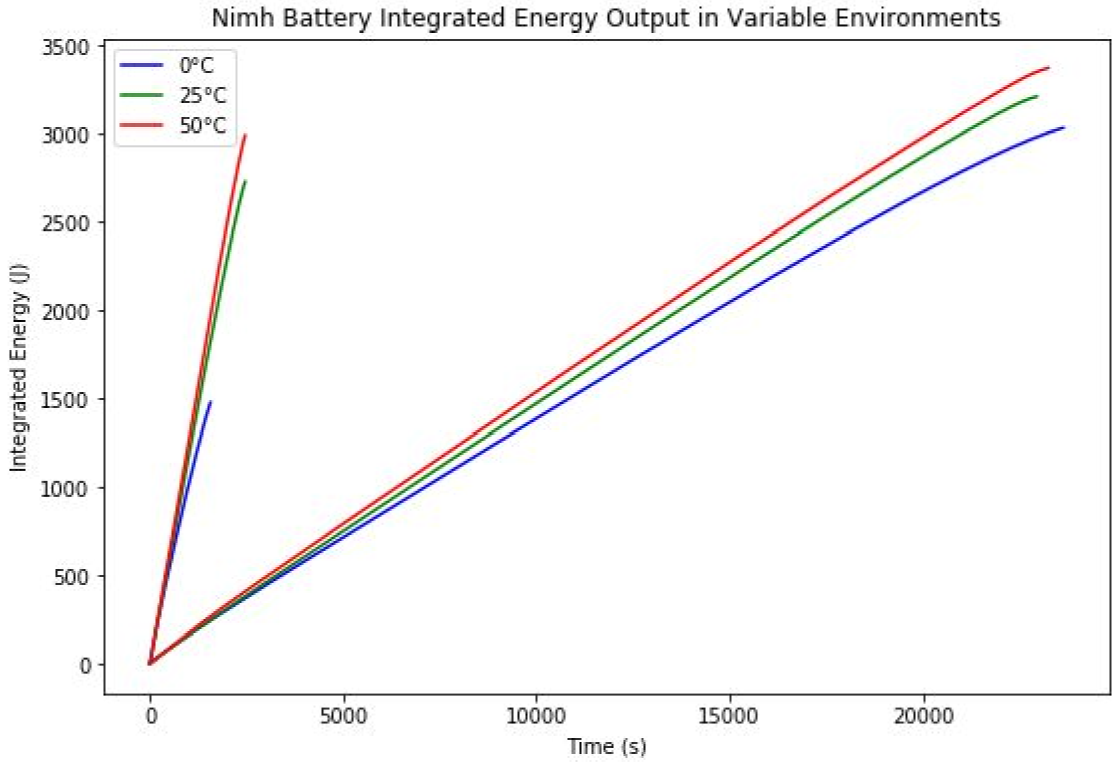

Figure 12c: The integrated energy output of Ni-MH batteries with respect to time

Figure 12c shows the graph of energy output of Ni-MH batteries of two loads and three conditions. We can observe that the slope of the curve in a higher temperature environment is steeper. The battery in 0° C condition under 1Ω load has output significantly less energy compared to other conditions under the same load. Other than the single outlier, the other conditions have similar effective energies to the other temperatures with the same load, but the hot temperature performs the best still.

Lithium Ion

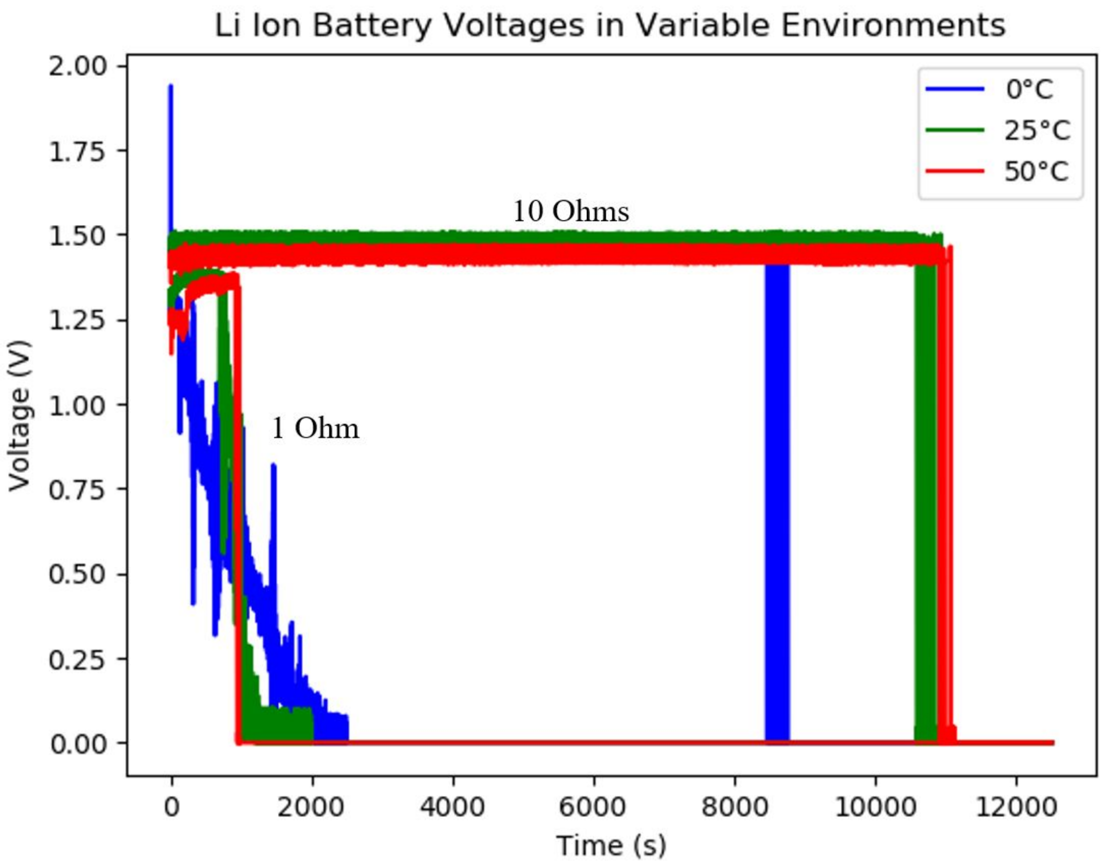

Figure 13a: AAA Lithium Ion battery results

Figure 13a above shows the results from the measurements taken on the AAA Lithium Ion batteries. The lithium ion batteries have a unique behavior in that under 10Ω, they maintain an extremely steady voltage with only minor variations as opposed to decaying over time like the other batteries. This is due to the internal circuitry that maintains a 1.5V nominal voltage output rather than the natural 3V nominal voltage from traditional secondary lithium batteries. Additionally, the data in figure 13a only shows measurements taken until the battery voltage drops to zero. In figure 13c, the rest of the data is displayed.

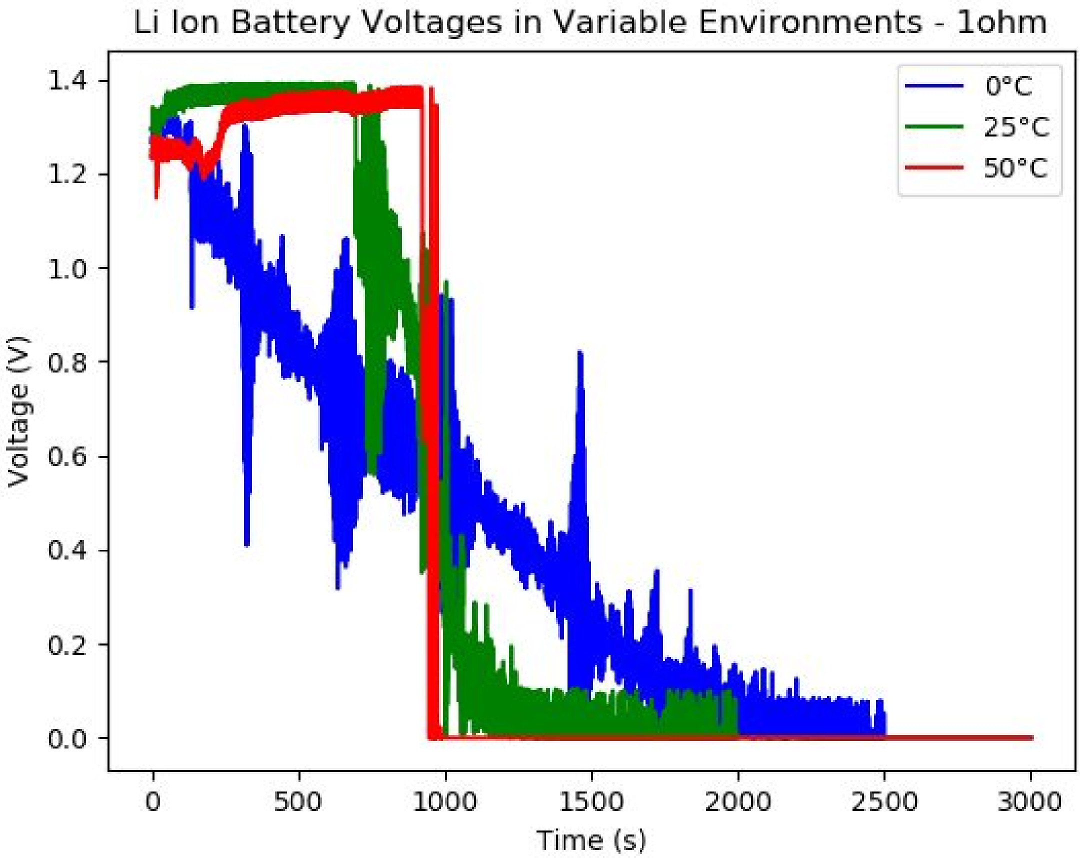

Figure 13b: AAA Lithium Ion battery results with 1Ω load

Figure 13b is the results of measurements of AAA Lithium Ion batteries zoomed in for displaying the voltage data under 1Ω load. The results from the lithium ion batteries under 1Ω load are very strange as they do not appear to be useful under these conditions at all. The cold temperature instantly decays in an unstable fashion, the other two conditions maintain nominal voltage briefly before also decaying in an unstable fashion with only the hot temperature resembling the instant voltage drop like the batteries under the 10Ω load. Notably, after the measurements were taken, the battery in the hot temperature had slightly warped as the adhesive that held the exterior wrapper to the rest of the battery began to melt in the hot environment. This only happened to the 1Ω load battery which will be discussed in figure 15 because the battery temperature heated up to 68°C due to the internal battery temperature increasing drastically. Additionally, the cold battery under a 1Ω load made a soft "ticking" sound after measurements were taken.

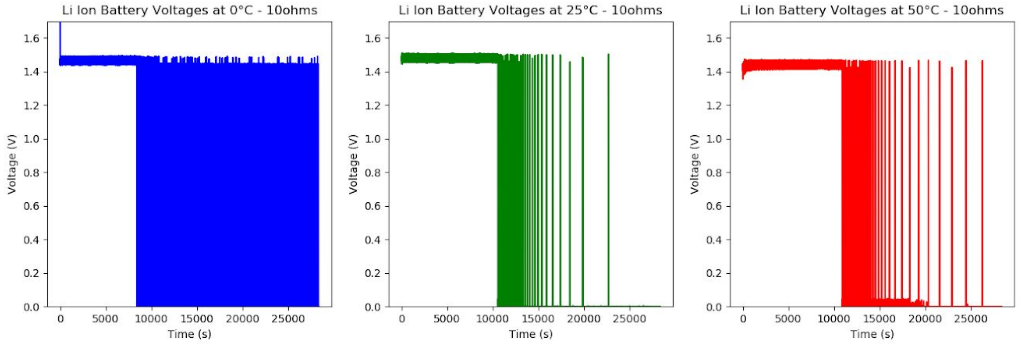

Figure 13c:

Figure 13c shows the complete data collected from the lithium ion batteries under 10Ω. Note that the time scales are all the same for each graph. After the batteries die, they sporadically jump back to nominal voltage for a few seconds before dying again and the time intervals between these jumps increase over time as well. The reason for these random surges in voltage have to do with the internal circuitry of the batteries somehow resurging a brief 1.5V potential.

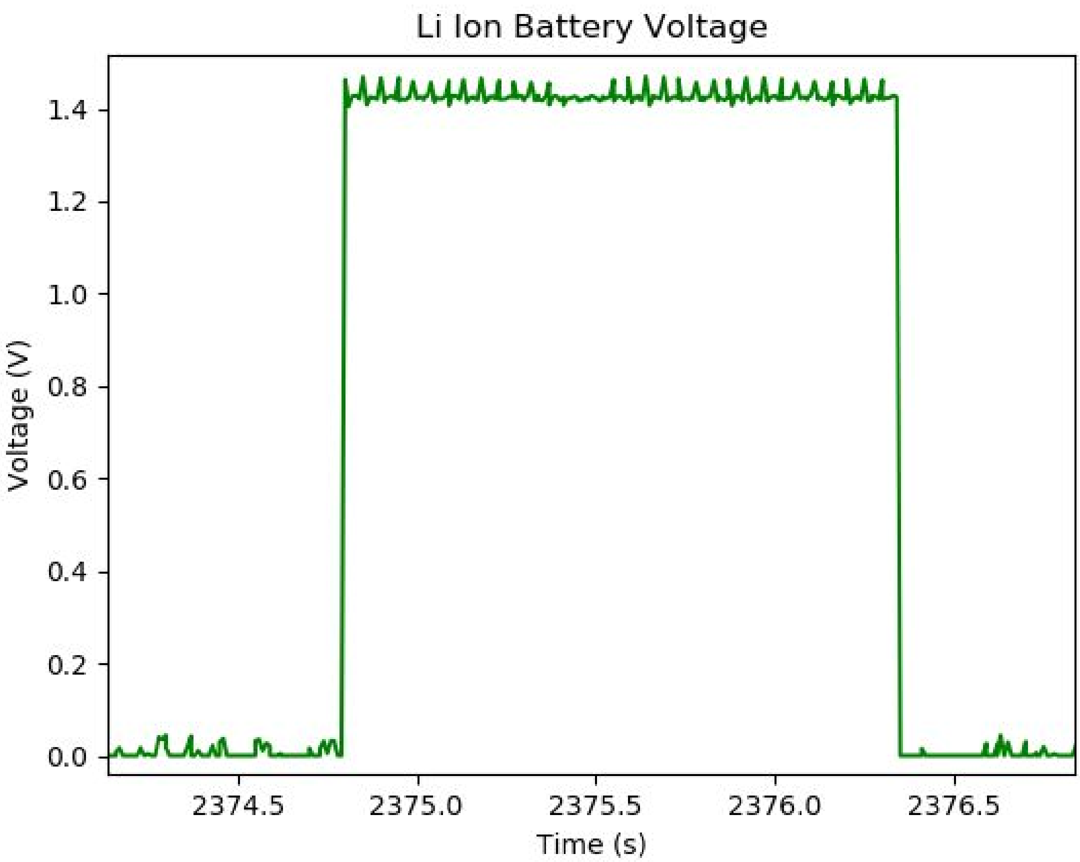

Figure 13d: AAA Lithium Ion battery measured at high frequency

From the above figures of AAA Lithium Ion batteries, we observed unusual behavior of voltage. There are violent fluctuations before the batteries are completely drained. The fluctuations often range from zero volt up to its initial voltage. We further examined this behavior by measuring the voltage at a much higher frequency. Figure 12d is zoomed in from the result of this examination. Note the time scale of figure 12d is zoomed in on a single spike from the room temperature battery. This shows that the voltage peak is instantaneous and not gradual.

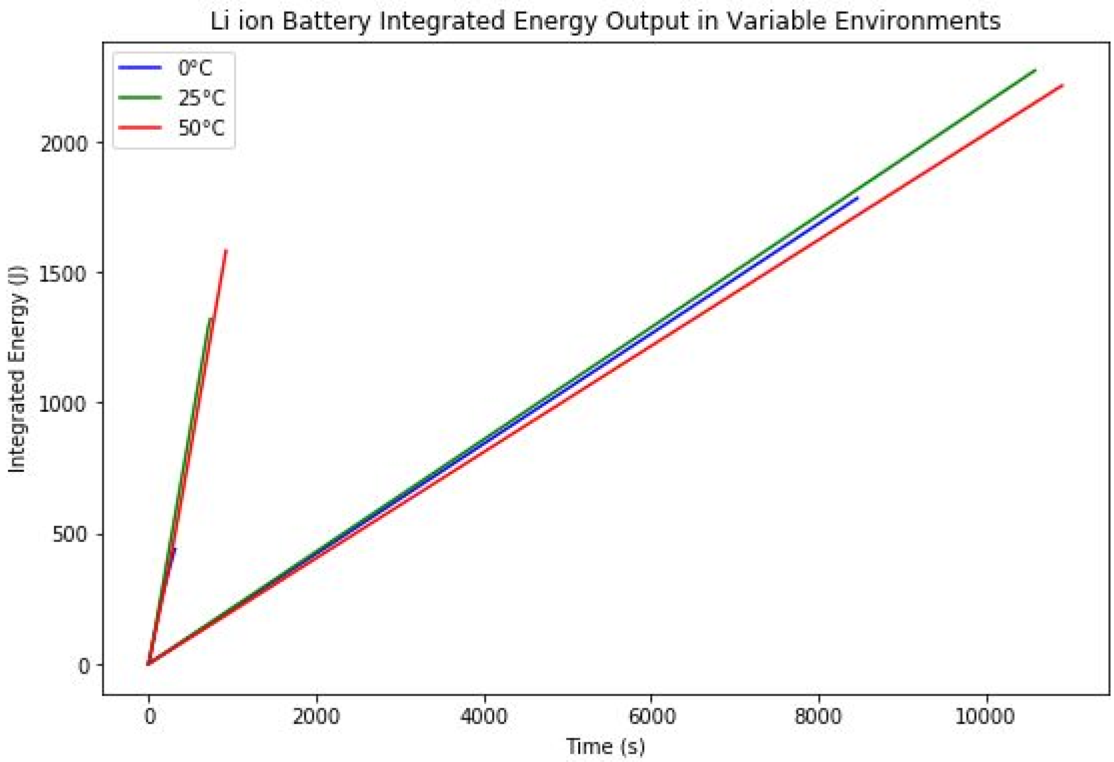

Figure 13e: The integrated energy output of AAA Lithium Primary battery with respect to time

Figure 13e shows the graph of energy output from AAA Lithium Primary batteries of two loads and three conditions. We can observe that the curves of 1Ω load are steeper than the curves of 10Ω load. Plotting is cut once the voltage output becomes unstable and drops below 0.8V although the voltages may jump back higher later, because we think that the batteries are not considered functioning properly afterwards.

Lithium Coin Cell

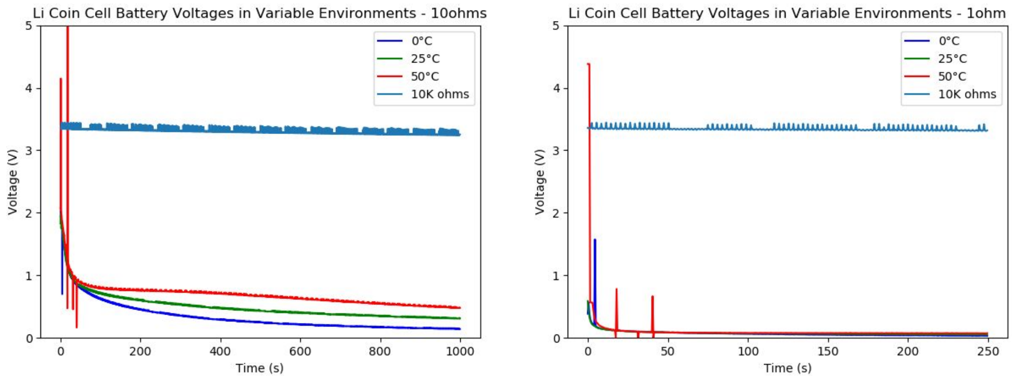

Figure 14: Lithium Coin Cell battery results. Note: time axis are not to scale in order to show results

The data in figure 14 demonstrates the errors that occur when trying to operate outside of the manufacturer's specified conditions. The coin cell batteries are limited in discharge current to 390μA, however we tried to pull 3A and 0.3A from them. As a result there was an initial voltage spike as the batteries were attached to the circuit followed by an immediate drop in voltage and a slow decay of the remaining voltage that the batteries provided to the circuit.

Battery Temperature

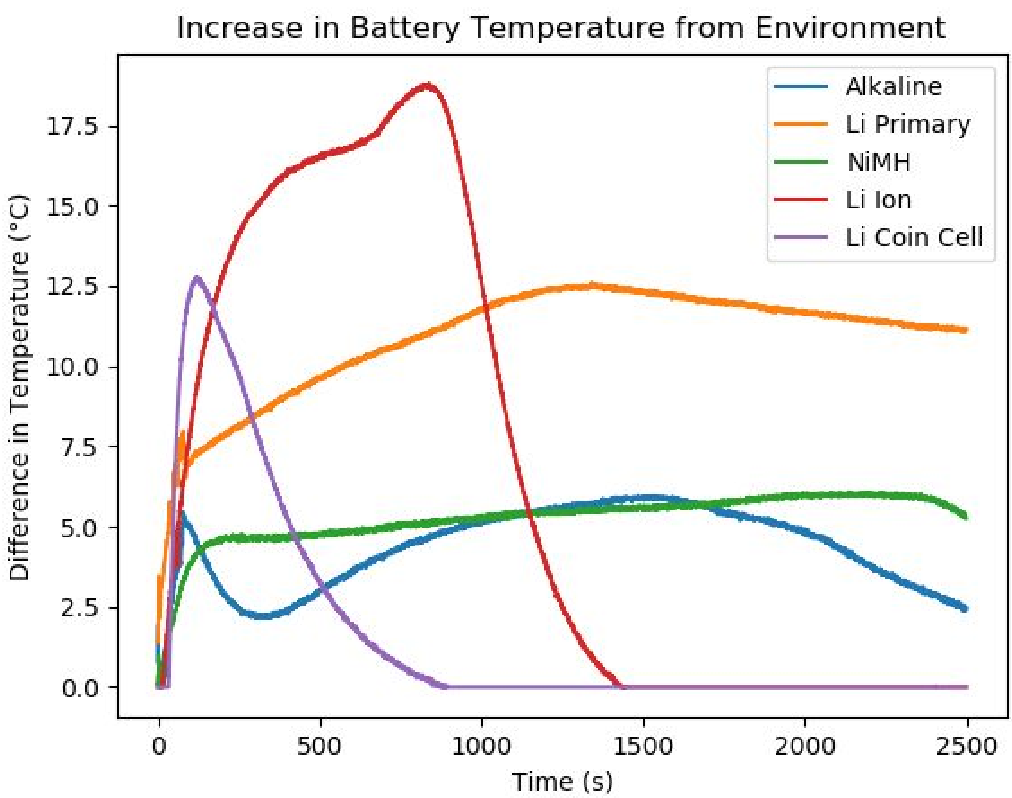

Figure 15: Difference in temperature between environment and 1Ω batteries during discharge

At low resistance (1Ω), the batteries' temperatures are observed higher than the environment temperature. This is due to the lower resistance providing a much higher discharge current. The most significant increase of battery's temperature is observed in the Lithium ion rechargeable battery. The effects of the temperature increase were strong enough that the adhesive holding the plastic wrapper to the battery begins to melt. This would mean that discharge current would not only affect energy capacity but could also potentially lead to issues relating with heat (combustion). The increased battery temperatures results in higher internal resistances which means less efficiency.

IV Discussion

Condition\Type	Alkaline	Lithium_Ion	Lithium_Primary	Ni_Metal-Hydride
50°C 10Ω 50°C 1Ω	4164 J 1627 J	2214 J 1582 J	6399 J 4605 J	3373 J 2991 J
25°C 10Ω 25°C 1Ω	3282 J 1279 J	2271 J 1320 J	5765 J 4541 J	3211 J 2727 J
0°C 10Ω 0 °C 1Ω	2047 J 406 J	1783 J 439 J	5597 J 3389 J	3033 J 1476 J

Table 3: Integrated energy output (Joules) of batteries before battery voltage drops below 0.8V.
For Lithium ion batteries, the calculation is cut once the voltage output becomes unstable and drops below 0.8V although the voltages may jump back higher later.

To analyze what these results might mean in terms of effective energy capacity, the above table can provide some insights. One important thing to note is that the 1Ω circuit consistently led to lower total energy output. This implies that discharge current does indeed have an effect on effective energy capacity. Additionally, the graphs in the previous section titled 'Results' demonstrated that the circuits with 1Ω consistently led to faster voltage drop offs and discharge rates.

Interestingly, hot environments led to higher total energy outputs but the effect was often less significant when compared with colder environments. Further implications of these numbers will be discussed in the 'Conclusions' section.

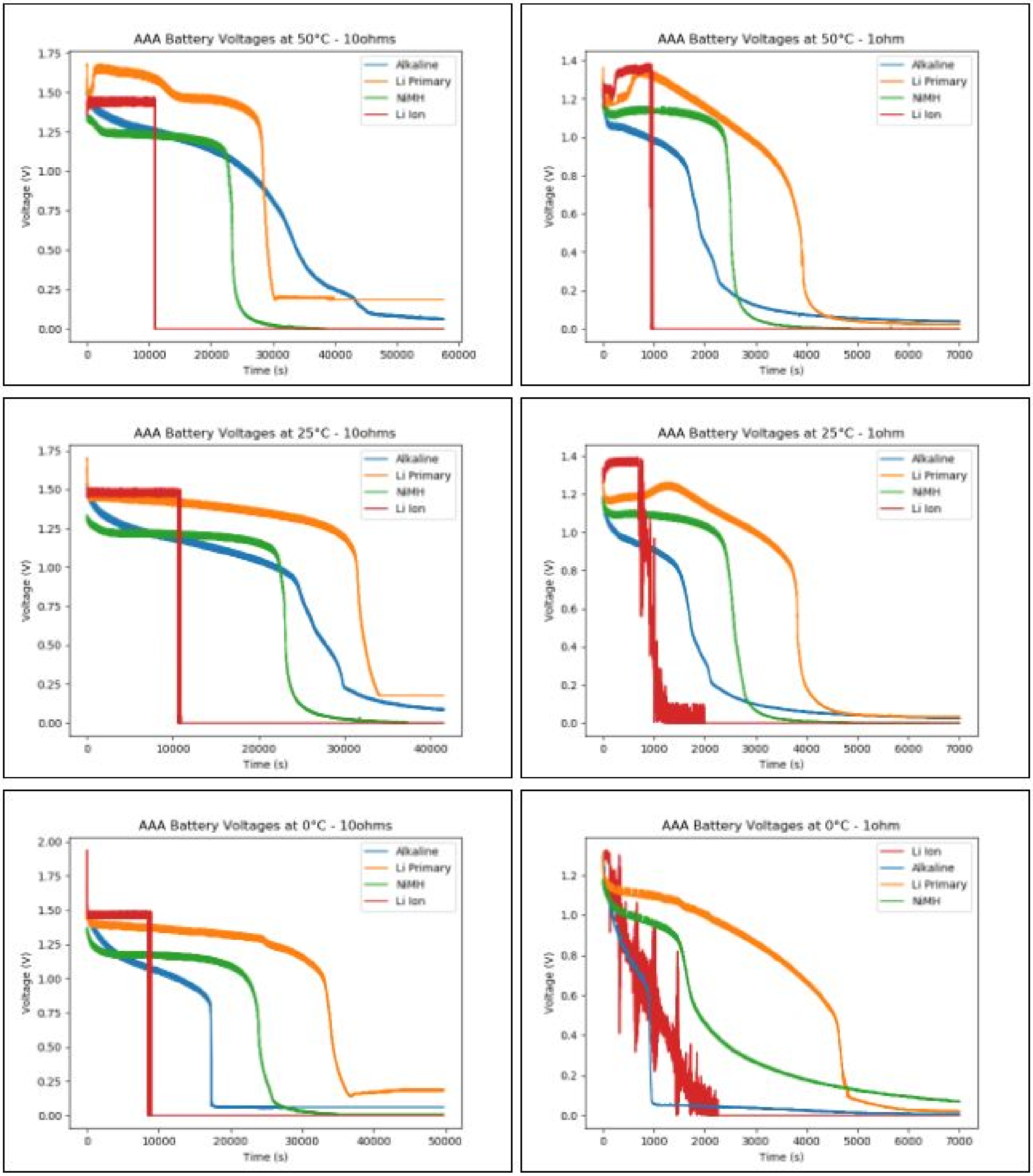

Figure 16: Collection of all of the different test conditions graphed separately. Note: Axis are not consistent between graphs in order to compare different battery results more easily

Figure 16 compares the results from each of the batteries in all the test conditions. It is clear from each of these graphs that the lithium primary consistently took the longest to reach the nominal voltage in every test condition suggesting that it is the most efficient battery chemistry. Under the 1Ω, the NiMH batteries performed second best. They also have the least voltage decay while operating besides the lithium ion batteries. The alkaline batteries underperformed in all test conditions except under 10Ω in the room temperature and hot environments where it was on par with the NiMH batteries. The lithium ion batteries died the quickest in all test conditions and were inoperable under 1Ω. However, due to the internal circuitry controlling the voltage output, they maintained the most consistent voltage before dying.

Coin Cell Investigation

When data is plotted it appears that sometimes the batteries are already dropping in voltage by the first data point. For example, the coin cell data shows voltage values that are not close to the manufacturers label of 3V; the highest recorded voltage was 2.2V. The coin cell batteries had especially quick energy lifetimes, and the data even suggests inconsistent results with all other batteries. There is probably some error involved in coin cell DAQ and resistive loads. The quick voltage drops can probably be explained by our larger than usual current draws which place extra stress on our batteries and discharge them much faster than anticipated.

The measurements for coin cells can be made better by using a circuit with a much higher resistance to provide a current that's closer to the manufacturer's specifications. The discharge current at the moment pulls too much charge out of the battery at once. It is not suitable to perform at our current experimental setup as even our DAQ can't get an accurate reading of voltage. While we were planning on incorporating data from coin cell batteries, our currents made the batteries too unstable, and no certain conclusions can be drawn. For this reason, they have been left out from the rest of the lab report.

Lithium-Ion

Lithium-ion batteries also demonstrated a weird behavior of oscillating between a maximum and 0V. This is due to the internal circuitry of the lithium ion batteries trying to maintain a constant 1.5V nominal voltage. The oscillating data can be made better by taking averages as can be seen in the 'Results' section for Fig. 12.

V Conclusions

Based on these results, current draw and temperature differences have an influence over the effective battery energy capacity of common AAA batteries. Larger discharge currents consistently led to a lower measurable, starting voltage and faster overall drain. The batteries also showed a difference in the overall total energy output. When the energy outputs of the 1Ω and 10Ω circuits were compared, the overall energy was higher in the 10Ω circuit consistently. Higher resistance would lead to a lower overall current draw, and this would provide more optimal performance and efficiency as long as current draw is not too low. While results were consistent with the hypothesis that there exist optimal parameters (temperature & discharge current) for battery operations, coin cell data is not exactly conclusive and those issues have been discussed above.

The effect of temperature is apparent in two ways. Firstly, environmental temperature influences the rate of voltage drop. From the graphs in the results section, we observe that in each setup of circuit, the batteries have about the same initial voltage upon plugging into the circuit. Then, in environments with lower temperature, the battery voltage drops faster and reaches lower voltage values much faster. Secondly, the environmental temperature influences when the sudden drop of voltage occurs. Notably this influence depends on the battery type. For alkaline batteries, lower temperature results in the sooner occurrence of the sharp drop; for lithium primary batteries, on the other hand, lower temperature postpones the occurrence of sharp drop; for nickel-metal hydride batteries, the influence is not significant.

But temperature data did not necessarily show a major effect from hot environments. When the total energy output was calculated, hot environments even seemed to provide more effective energy. However, the effects from hot environments were not as strong as colder environments. This suggests that colder temperatures may have a much more noticeable effect on effective energy capacity. On the other hand, room temperature and warm environments usually stayed relatively close to each other with only slight differences that were not necessarily obvious enough to draw any major conclusions. It appears that room temperature and 'hot' (50°C) environments provide the most 'optimal' total energy output.

Temperature produces some mixed findings, but overall the data seems to suggest that inefficiencies appear once batteries deviate from room temperature conditions and away from the manufacturer specified current draws. The colder environment consistently led to lower total power outputted when compared with room temperature and hot data. There were also interesting effects on the shape of the voltage curve for the cold data. Some of the batteries had unstable voltage graphs which provides evidence that a battery discharging in the cold could potentially demonstrate unwanted behavior for people concerned with achieving effective energy capacity.

Overall, the data shows some trends and patterns from which conclusions about effective battery energy capacity can be made.

VI References

"AnalogRead()." *Arduino Reference.*

Bates, Mary. "How Does a Battery Work?" *MIT School of Engineering.* 1 May 2012

"Digital Plug & Play Infrared Thermometer in a TO-Can." *Melexis.*

"Energizer Lithium Coin Handbook and Application Manual." *Energizer.* 2018

"Energizer L92 Ultimate Lithium Product Data Sheet." *Energizer*.

"Energizer Rechargeable AAA-1000 (HR03) Product Data Sheet." *Energizer*.

Graham, Christopher Fox, and Lindsay D. "What Is the Seebeck Effect?" *WiseGEEK*. Conjecture Corporation, 14 Apr. 2020

Gudino, Miguel. "How Analog-to-Digital Converters (ADCs) Work." *Arrow.com*. 17 Apr. 2018

Li, Zhijiang. "Specifications for Non-Hg Alkaline Battery." *Shenzhen PKCELL Battery CO.* 1 Jan. 2000

MIT Electric Vehicle Team. "A Guide to Understanding Battery Specifications." Dec. 2008

Rengi, Donna, and C. Wilborn. "What Is a Thermopile?" *WiseGEEK*. Conjecture Corporation, 22 Mar. 2020

"TMP36 Data Sheet." *Analog Devices.*