Impact Of Discharge Current Of Rechargable NiMH Batteries On Charge Output In Accordance With Peukert's Law

Kerim Doruk Karinca, 001129-0041
Supervisor: Mine Gökçe Şahin

IB May 2015

Chapter 1

Abstract

This experiment report is based on the changing available charge capacity (electron count) of a battery by the average current demand, by using Peukert's Law. The battery capacity written on packaging wasn't found to be constant, as Peukert's Law states that high current demand from a battery decreases the number of electrons that the battery can provide. Thus, charge output and runtime aren't linearly correlated - current demands decrease the charge output in a curved fashion. The power that this curve is raised to is called the Peukert constant. This paper found the Peukert constant for GP 2700 Series Rechargable battery to be 1.174. The greater this constant is, the greater the electron losses.

Results are directly applicable to battery performance. Increasing currents are found to drain the battery exponentially (eg. doubling the current empties the battery not twice, but more than twice as fast). Thus, making energy-efficient mobile devices will not only save energy, but will make more potential energy available to the device. Most importantly, expecting to obtain the rated (advertised) battery capacity regardless of current is ungrounded, while capacity is a function of current draft abiding by Peukert's Law.

This report analyzes 10 trials of collected current and runtime data by changing current drafts (through varying resistances) to utilize the mathematical model leading to the calculation of the Peukert constant.

Chapter 2

Introduction

2.1 Background

Batteries have been serving as a compact source of electrical energy for the past 20 years, but it's not possible to speak of a major advancement after Sony's first lithium-ion battery in 1991. [1] The most prominent reason is that mobile device companies favor adding new features to their devices, which is commercially more attractive to a customer than an extended battery life.

Until then, it's best to focus on factors affecting the overall charge output of the common rechargeable battery, which is the primary motive behind the selection of topic for this article.

2.2 Objective, research question and phenomenon explanation

This experiment studies the charge output of the GP 2700 Series 1,2V NiMH rechargeable battery on a circuit given one independent variable: number of parallel connected batteries of same type.

Parallel connection of batteries allows the overall internal resistance of batteries to decrease. Although the internal resistance of the battery is calculated to be negligibly small, the accuracy of the data increases as more batteries are connected in parallel in further trials. Ohm's Law (see 1.3) accounts for the decrease in overall resistance in parallel connections. Moreover, applying different resistances could incur varying uncertainties associated with the resistances, so keeping an unchanged resistance was found to be more convenient.

The phenomenon behind Peukert's Law is chemical. The reactants in the battery need to travel within the battery to complete spontaneous reactions that produce energy. But demanding high currents do not allow sufficient time for chemicals to reach their target, thus the charge output never agrees with the theoretical value. [5]

To focus more on the physics of the phenomenon instead of chemistry, the mathematical model of Peukert's Law will be compared to collected data of electrical nature.

In this experiment the batteries are rated as 2600mAh (mili amperes times hours), which means the battery should provide a theoretical current of 2.6A for 1 hour, or 5.2A for 30 minutes. According to Peukert's Law, there will be less charge output in the latter condition because of the aforementioned reasons, thus in reality the battery is expected to die way before 30 minutes.

This experiment will calculate the Peukert number for the GP 2700 Series battery and calculate drops in charge output for varying currents. Calculating an appropriate Peukert number for this battery model can lead to a more accurate determination of the battery runtime in use. Real life applications of this phenomenon will allow the said "battery percentage" in electronic devices to yield more accurate "remaining runtime" results. Given the theory, the appropriate research question is as follows:

"How does the number of parallel connected batteries of brand GP 2700 Series 1,2V NiMH affect the charge capacity per battery, in accordance with Peukert's Law, within the same circuit with constant resistance applied, ambient temperature, battery age and charging time?"

INDEPENDENT VAR.	DEPENDENT VAR.	CONSTANTS
Number of batteries (1 to 9	Charge capacity per battery	External resistance of the circuit (10.2Ω)
		Ambient temperature (27°C)
		Cable length (see method)
		Cable cross-section diameter (1.4mm)
		Battery age (11 months old)
		Charging time (until full charge, which is 12 hours)

Figure: Variables of the experiment. Constants such as battery age and temperature affect battery capacity and internal resistance respectively, thus should be kept constant.

2.3 Description of relevant terms and theories

$$V = I \times R$$

Figure 2.1: Formula of the Ohm Law [3], where;

V: the electrical potential between two poles in volts

I: the current flowing through the main branch in amperes

R: the resistance against the current in ohms (Ω)

$$P = I \times V$$

Figure 2.2: Formula of the Joule's Law [4], where;

P: the power of the battery in Joules per second, for;

I: Current in amperes.

V: electrical potential in volts.

P can be replaced by J/t (Joule / second) so that the total energy output over a period of time can be expressed as follows.

$$J = I \times V \times t$$

Figure 2.3: Derived formula of the absolute energy output of a battery.

Since the electrical potential in volts (V) is defined by the amount of energy in joules (J) carried per unit charge in coulombs (C), $I \times t$ alone will give the total amount of electrical charge stored in the battery in coulombs:

$$J = I \times \frac{J}{C} \times t$$

$$J \times \frac{C}{J} = I \times t$$

$$C = I \times t$$

Figure 2.4: Derived formula of the charge capacity of a battery. [4]

$$A \times t = U$$

Figure 2.5: C-rate of discharge explained in terms of time and charge capacity, where;

A: the C value in mili-amperes for the given battery capacity and current

t: time in hours

U: charge capacity in mAh

The theoretical capacity of one battery used in this experiment is 2600 mAh (mili-amperes times hour), already written on its packaging.

C-rate: C-rate is the magnitude of current drawn from the battery with respect to its charge capacity. Therefore, C-rate is a battery specific coefficient of current, but does not replace the current itself.

A current of 1C signifies that this current will empty a fully charged battery in 1 hour. 2C signifies twice that current for the same battery, meaning that discharging a battery at 2C means discharging it completely in 30 minutes. Consequently, a battery discharged at 0.5C will last 2 hours.[2] C rate is inversely proportional with discharge time, where battery capacity is the constant. Refer to Figure 2.5.

The charge capacity of the battery used for this experiment is 2600 mAh. Thus, a current of 1C for this battery equals 2600 mA.

Although they are not part of the scientific notation because of their relativity, C-rates allow the experimenter to signify what the measured current means relative to the entire capacity of a battery. 10 amperes of current will discharge a 2600 mAh battery in less than 15 minutes, but a 20000mAh battery will last 2 hours under the same current. The C-rates will help point out the difference, for C-rates will be different for these two batteries, which could provide convenience in explanation.

Most importantly, although the C-rate system works fairly well with current values close to each other, Peukert's Law is there to show that there's no linear correlation. Thus C-rates cannot be used directly. Peukert's thesis, favored in this experiment, to the C-rate understanding of battery capacity is like how quantum relativity is to Newton's physics. The latter in both are applicable only in narrow spectrum.

Nevertheless, the C-rate is at least important for safety during experimentation, as discharging a battery at currents higher than 10C will cause many batteries to explode.

Self-discharge: Batteries discharge themselves even when they're not in use, or used at low currents. Although the rates are slow, energy loss becomes significant over long periods of time.

When batteries are not used for long periods of time, some electrons get past the separator between the positive and negative electrodes to complete battery half-reactions (see Figure 2.6). In other words, there forms a short circuit inside the battery other than the circuit the battery is connected to. Thus the separator has to have special permeability properties to prevent energy-carrying electrons from passing to the positive electrode spontaneously. This process is called self-discharge, and is undesired, for the battery's potential energy goes to waste before it could've been put to use. [7]

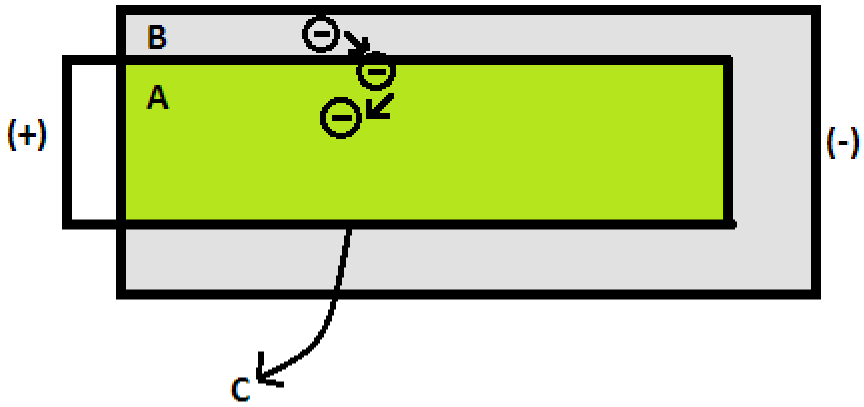

Figure 2.6: Electrons passing through the separator of experimented GP battery, where;

A: Positive electrolyte $Ni(OH)_2$

B: Negative electrolyte KOH + NaOH

C: Separator (usually glass) [8]

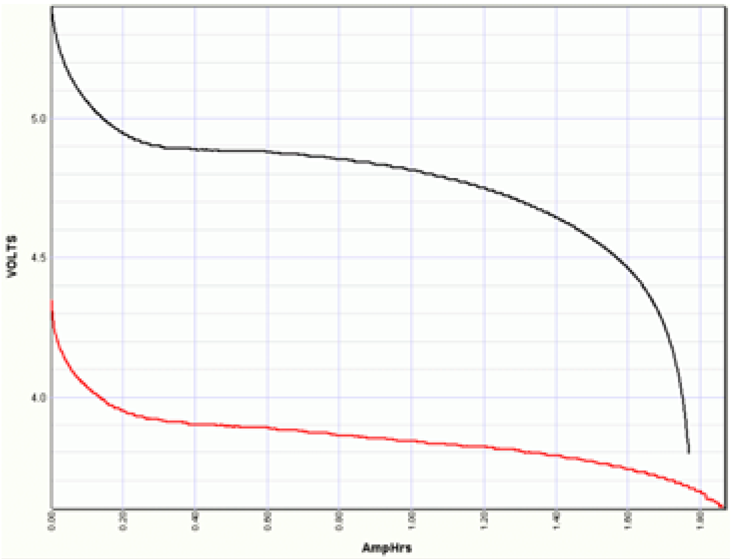

Figure 2.7: An example of voltage curves. [9]

Voltage curves: Against all theoretical assumptions made (usually in examinations), the voltage provided by a battery source is never constant, and forms a curve over its course of discharge as in Figure 2.7.

The voltage is plummeting at high and low ends of the remaining charge of the battery capacity. The rated value usually comes from the mid-range where the slope of the function is nearest to zero. Although voltage values won't be utilized, data observation shows that the current follows a similar path to that of voltage. For best experimental results, average current values will be obtained and used where necessary. But to determine the average values properly, the proper cutoff point of the graph needs to be known, so that the averages do not show lover than they actually are.

Cutoff voltage is the voltage value below which it's assumed that the battery is no longer holding charge that could be of use. There will always be a remainder of charge in the battery, but if the voltage cannot suffice to operate a device, then that operation voltage of the battery at the time is said to be below the cut-off voltage.

For example, the cutoff voltage for the blue function line in Figure 2.7 is 3.8V. Because the proceeding data is discarded.

The cut-off voltage for NiMH batteries is commonly 0.8V, given that the battery is rated 1.2V on packaging. NiMH batteries cannot deliver sufficient energy for operation below this point. The cut-off voltage will especially be important when averaging the voltage value for a particular repetition, because not specifying a bottom line for voltage can lead to too low average values.

Most importantly, discharging batteries beyond their cutoff voltages can cause permanent battery damage. Modern smartphones and some other mobile devices have voltage monitors so that the device automatically shuts down above its cutoff voltage when the battery is low. But there is no such automated mechanism in this experiment, so manual monitoring is mandatory.

Peukert's Law was already explained in 1.2 in terms of its practical implications. The mathematical modeling of the function is below.

The constant k is a number greater than 1 and depends on the battery brand and chemistry, but NiMH batteries are expected to have a constant smaller than 1.3.

Unfortunately there exists no previous research on the Peukert's constant of the GP

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

Figure 2.8: Equation of Peukert's Law [6]

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

Figure 2.9: Rearrangement of variables of Peukert's Law to solve for "k", where;

t: discharge time in hours, which will be measured

H: rated discharge time in hours, to discharge the battery when the battery capacity on the packaging by the manufacturer is measured, which is 20 hours for the experimented battery

C: rated capacity in miliampere-hours (stated as 2600 mAh on packaging)

I: actual discharge rate in miliamperes, which will be measured

k: Peukert's constant, which is the dependent variable

2700 Series battery. The accuracy of the data will depend on expecting a value smaller than 1.3, and preferably closer to 1, but not below 1.

Chapter 3

Experiment Setup & Data Processing

3.1 Experiment setup

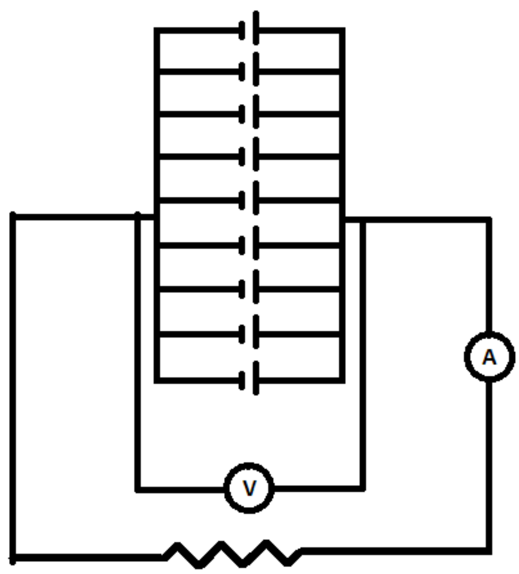

Figure 3.1: Sketch diagram of the circuit for trial #9. Each trial index number corresponds to the number of parallel connected batteries.

In this experiment 3 repetitions took place for each trial from #1 to #9.

A word on the limitation that entails connecting too many batteries:

When there were 9 batteries in parallel in trial #9, the current draft per battery was too low to observe any loss that comes with high current draft, which would be in favor of Peukert's Law by producing contrasting data towards charge losses in earlier trials. But discharging at low currents has increased the experimentation for trials with up to 9 batteries in parallel to take longer than 40 hours, which could introduce a new factor: self-discharge rate.

As explained in 1.3, self-discharge occurs when battery is on shelf or discharged at very slow currents. Since Peukert's Law does not account for this phenomenon, experimenting at very low currents could cause results that do not follow the expected trend.

Although self-discharge rates are too low for NiMH batteries, no more than 9 batteries at once were experimented, for adding more batteries in parallel would reduce the current demand per battery even further, which would pave the way for self-discharge rates to become a significant systematic error.

3.2 Material list

- 9 x GP 2700 Series 1,2V NiMH rechargeable battery
- 9 x battery holder
- 1 x 5m cable with thickness of 1.4mm
- 1 x Vernier voltage probe ($\pm 0.001V$)
- 1 x Vernier current probe ($\pm 0.0001A$)
- 1 x room thermometer ($\pm 0.1°C$)
- 1 x Vernier LabQuest data logger
- 2 x $5.1\Omega \pm 5\%$ resistors
- 1 x GP Fast Battery Charging Station
- 1 x scissors
- 1 x USB storage device having minimum 100 MB free space
- 1 x duct tape roll
- 1 x 1m ruler certain at least to the nearest cm
- 1 x countdown timer certain at least to the nearest second

3.3 Method

1. Acquire cable and cut two pieces of cable of length 0.5 m. Use the ruler for measurement.
2. Cut one 0.5 m cable in half with scissors. Use ruler for measurement.
3. Connect both 0.25 m cables to the current probe, and one end of one cable to one resistor.
4. Connect resistors together by twisting their metal ends.
5. Connect the 0.5m cable to the other end of the resistor pair which is not tied to the current probe.
6. Cut 5 cm cables as much as necessary, and connect each to both ends of each battery holder. Use duct tape to adhere the cables to the metal ends of the holders. Ensure that holders are all facing the same side.

7. For convenience, you may consider duct taping the complete circuit on a board at this point. This is optional.
8. Twist the cables of 5 cm together in groups of 3, and then twist the 5 cable groups at each end of the battery holders between each other to form a main branch of current.
9. At both ends of the main branch in step 8, specifically to the points which are nearest to the batteries, connect the voltmeter probes in parallel.
10. Plug in the voltage and current probes to the data logger.
11. Charge one battery for 12 hours. The fast battery charging station tells when the battery is full with a green light.
12. Prepare the data logger by setting up the recording duration to 40 hours and directing the data storage path to the external storage device. Let recording rate be 120 collections per hour.
13. Place one battery into one of the battery holders and press “start” on the data logger.
14. Check bi-hourly the voltage value and the room temperature from the thermometer. When the voltage is less than 0.8V, press the stop button and wait a moment until data is saved.
15. If temperature fluctuations greater than 2C are observed during bi-hourly checks, abort the repetition. Discharge the battery(s), discard the collected data and start over. Heat/cool the room until the desired temperature is read on the thermometer.
16. Backup every run to another storage device and/or to the cloud immediately.
17. Repeat steps 11-15 for taking 3 repetitions for each trial, and by increasing the number of batteries at every trial. Reusing the same battery will not alter the collected data significantly to the degree of causing a systematic error. But if a battery is not going to be used for a while, provide a cool storage environment (eg. away from direct sunlight).

3.4 Data collection

Peukert's Law was already introduced in Figure 2.3I:

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

"C" is 2600 mAh for this battery. "I" would be calculated as the average current. "H" is rated discharge time in hours that was already discussed under Figure 2.3. "t" is duration, which is raw data itself.

Some relevant experiment-time qualitative observations and unexpected circumstances:

- The batteries followed the voltage curve as expected.
- Batteries in specific battery holders provided smaller current readings because of insufficient contact area between cables' junction points. Necessary consolidations by additional cable and duct tape use have been applied before experimentation.
- Trials 6 and 4 had to be repeated for changes in temperature greater than 2C, and were repeated. But the discarded data (not included) was also processed, and was found to be in agreement with the rest of the data. Although temperature is posed as a significant factor in battery performance, changes up to 5C happen to be insignificant for NiMH battery performance. It's also probable that the coating of the battery insulates the battery against temperature changes, but there's no practical way of measuring internal battery temperatures.
- Outside the normal course of experimentation, the internal resistance was tested under two different resistances and calculated using Ohm's Law.

  $$\frac{1.333V}{0.1301A} = I_R + (10.200 \pm 0.510\Omega); I_R = 0.045\Omega \pm 0.510$$

  $$\frac{1.324V}{0.2550A} = I_R + (5.1 \pm 0.255\Omega); I_R = 0.092\Omega \pm 0.255$$

  That the internal resistance of each battery is found to be less than 0.1Ω made it negligible in calculations.
- Every waking hour of this experiment was powered by Nescafé and Turkish tea.

3.5 Data management

1. If applicable, the raw data below the cutoff voltage (0.8V) was trimmed.

2. The average current value for every trial and repetition was calculated by Excel 2013, and this value was divided by the number of batteries used to evaluate average current draft per battery, referred to as "I". (Table 3.1)

3. The function in Figure 2.9 was utilized using Excel to calculate "k", plugging in the calculated "I" value (see previous step) and the runtime "t" for every trial and repetition. The values "H" and "C" were already determined to be 20 hours and 2.6A respectively in the introduction. (Table 3.2)

4. The average of "k" values in repetitions for each trial (and every other processed data) was calculated using Excel. (Table 3.3)

5. The final, average "k" values were presented in a table. Standard deviation and uncertainty by range were calculated.

3.6 Calculations

3.6.1 Data Processing

Table 3.1: Average current draft per battery in amperes.

	Repetition 1	Repetition 2	Repetition 3
Trial 1	0.4628	0.4618	0.4613
Trial 2	0.2517	0.2514	0.2513
Trial 3	0.1634	0.1631	0.1630
Trial 4	0.1278	0.1276	0.1274
Trial 5	0.0952	0.0950	0.0948
Trial 6	0.0989	0.0984	0.0988
Trial 7	0.0751	0.0750	0.0749
Trial 8	0.0699	0.0701	0.0697
Trial 9	0.0721	0.0720	0.0719

Table 3.2: Calculated Peukert's constants "k" for every trial and repetition.

	Repetition 1	Repetition 2	Repetition 3
Trial 1	1.118	1.137	1.148
Trial 2	1.135	1.171	1.182
Trial 3	1.520	1.576	1.611
Trial 4	1.093	1.013	0.962
Trial 5	1.130	1.071	1.011
Trial 6	1.327	1.261	1.285
Trial 7	1.197	1.169	1.153
Trial 8	1.071	1.063	1.037
Trial 9	1.128	1.103	1.083

Two calculation examples for 3.2 are below.
Trial 2, repetition 1:
Time (t) = 9.450 hrs (from raw data)
Average current per battery (I) = 0.2517 A (see Table 3.1)

$$k = log_{\frac{C}{IH}}\left(\frac{t}{H}\right) = log_{\frac{2.6}{0.2517\times 20}}\left(\frac{9.450}{20}\right) = 1.135$$

Trial 6, repetition 3:
Time (t) = 28.392 hrs (from raw data)
Average current per battery (I) = 0.09845 A (see Table 3.1)

$$k = log_{\frac{C}{IH}}\left(\frac{t}{H}\right) = log_{\frac{2.6}{0.09845\times 20}}\left(\frac{28.392}{20}\right) = 1.261$$

Table 3.3: Average battery runtime, to be used in Graph 3.2

	Average battery runtime at trials (hrs / ±0.001)
Trial 1	4.747
Trial 2	9.289
Trial 3	14.003
Trial 4	20.483
Trial 5	27.989
Trial 6	28.533
Trial 7	38.142
Trial 8	38.533
Trial 9	38.412

3.6.2 Graphing

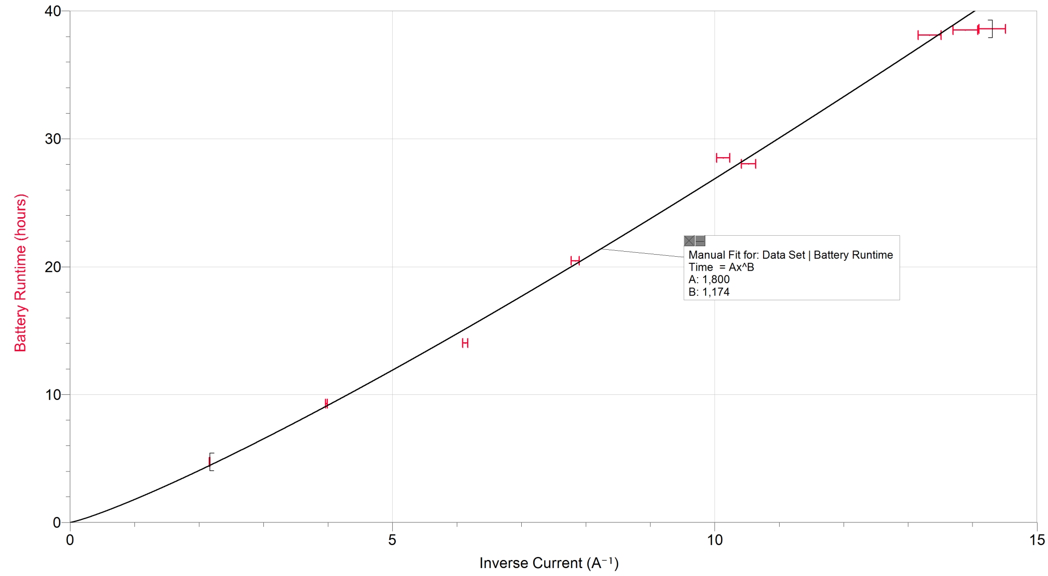

Figure 3.2: Correlation between inverse current (independent variable) and battery runtime. The exponent of the power best fit is the calculated "k" value.

The uncertainty for inversed current values were calculated by halving the difference between upper and lower boundaries:

$$\frac{\frac{1}{c-0.001} - \frac{1}{c+0.001}}{2}$$

Example for leftmost datapoint:

$$\frac{\frac{1}{0.461967-0.001} - \frac{1}{0.461967+0.001}}{2} = \pm 0.005$$

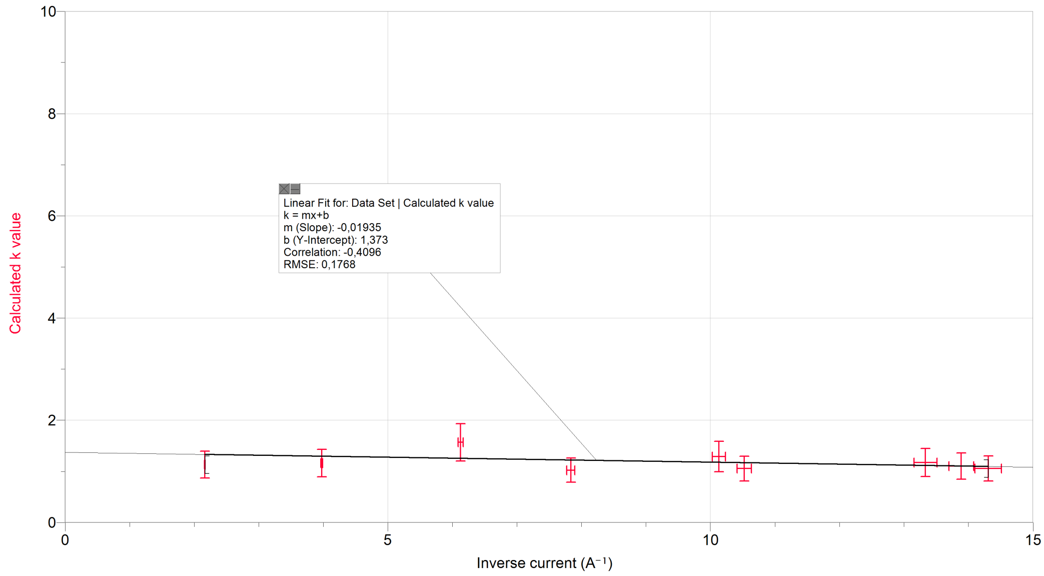

Figure 3.3: Shows the change in the calculated k value with inverse current. If the slope was not near to zero, then there would be a significant systematic error source that would amplify as the inverse current changed. But that the slope is -0.01 shows such a systematic error is out of the question. Further discussion, referencing this graph is in Conclusion. Uncertainty for "k" value is 23.2%, which was already calculated.

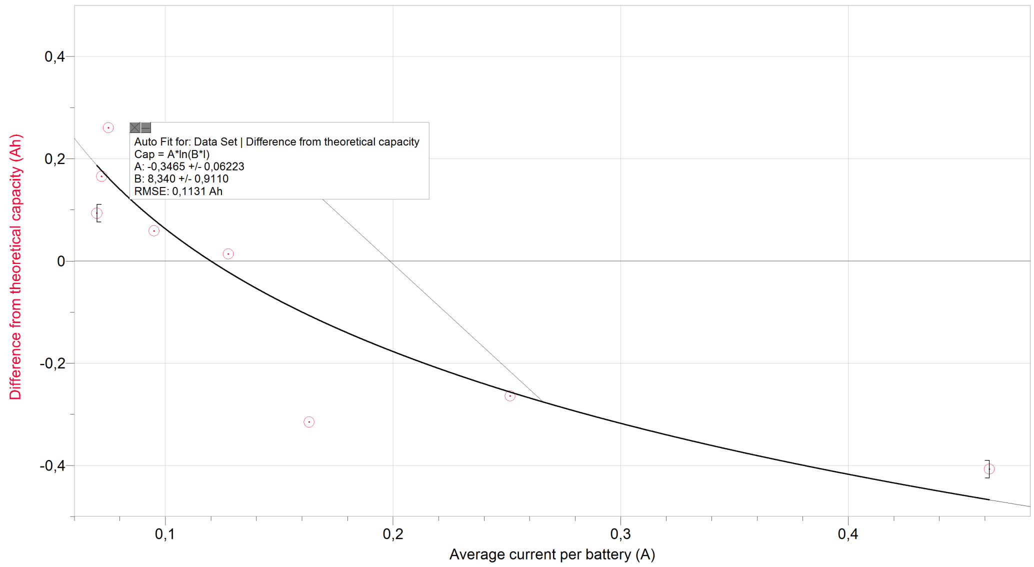

Figure 3.4: The difference of measured battery capacity from the rated capacity by changing average current. Despite the best-fit presented above, there's no healthy correlation to draw in this graph, since Peukert's Law is stated by the ratio between measured and rated capacity values, whereas subtraction is utilized here, hence no uncertainty bars are available. It was meant to show here that higher current demands imply lower measured capacity values, 0.12 Amperes being the point at which rated and measured capacities are equal (where the best fit meets x-axis). The y-axis error bars (Ah) were calculated by multiplying uncertainties of current (A) with the runtime (h). The runtime uncertainty was negligible (30 seconds uncertainty in 38 hours).

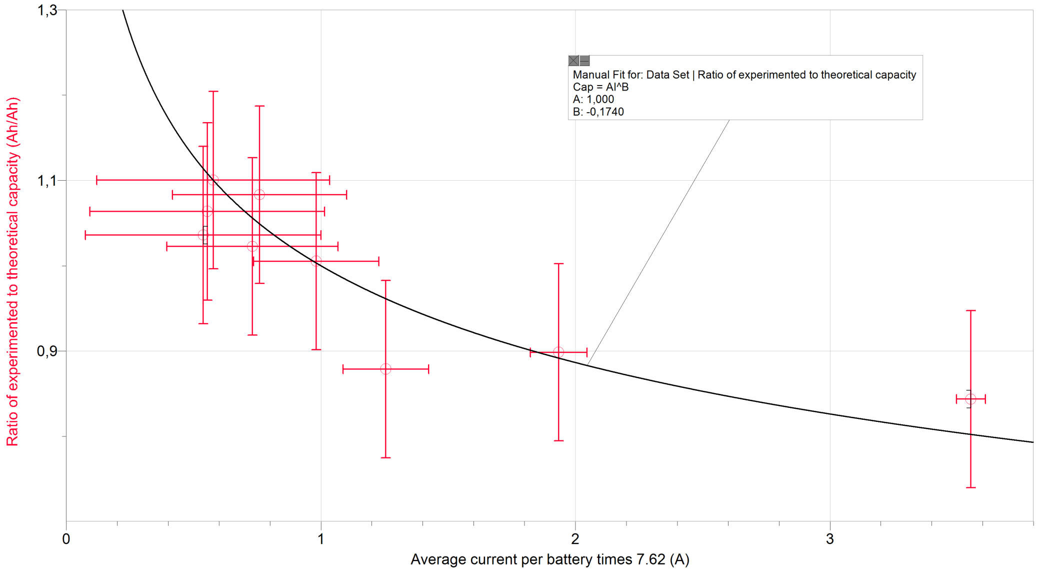

Figure 3.5: Recognizing the problem in **??**, the graph is reevaluated to conform to the ratio between experimented and theoretical capacity. Note that the x-axis has been multiplied by 7.62, which is H/C (20/2.6) in Peukert's Law. The mathematical model behind the best fit is:

$$I \times t = \left(\frac{C}{IH}\right)^{k-1}$$

Figure 3.6: Notation of Peukert's Law in terms of battery capacity instead of runtime. Since the I in parenthesis is inversed but the I in the graph is not, H/C was the multiplier instead of C/H and "k" was made negative, hence inversing twice does not alter the results. See the example below.

Example from a random trial:
Time (t) = 9.450 hrs (from raw data)
Average current per battery (I) = 0.2517 A (see Table 3.1)

$$I \times t = \left(\frac{C}{IH}\right)^{(k-1)} = \left(\frac{IH}{C}\right)^{-(k-1)} = \left(\frac{0.2517A \times 20h}{2.6Ah}\right)^{-(1.174-1)} = 0.891$$

Chapter 4

Conclusion

Rated charge capacity is the battery's expected charge capacity written on packaging, usually in the form of mAh. This experiment attempted to show that the rated charge capacity isn't a constant regardless of energy draft, and to calculate how the rated charge capacity changes with the current, by using Peukert's Law.

To clear up any confusion at start, it was already discussed that internal resistance is negligible, especially when the batteries are connected in parallel, for parallel connection of resistances decrease the overall resistance, making it even more negligible.

$$\frac{1.333V}{0.1301A} = I_R + (10.200 \pm 0.510\Omega); I_R = 0.045 \pm 0.510\Omega$$

$$\frac{1.324V}{0.2550A} = I_R + (5.1 \pm 0.255\Omega); I_R = 0.092 \pm 0.255\Omega$$

Figure 4.1: Recalling how internal resistance was calculated by direct proportion. Refer to experiment method for details.

The results have shown that a reasonable k value can be calculated, as the value lies within a reasonable precision, but there's insufficient literature to back the accuracy.

To recall, the calculated value of k is:

$$k = 1.174 \pm 0.2730(23.2\%)$$

It's sufficiently accurate to calculate a value of k smaller than 1.3, but any number closer to 1.1 would be more desired, while literature shows NiMH batteries normally have constants between 1 and 1.2. [13] However, looking at the uncertainty of the "k" value above, the value range in this case is between 0.9 and 1.44. There could be other factors responsible for the smaller capacity output (higher k value) and higher value ranges than expected.

Nevertheless, with a k value that equals 1.174, and almost all error bars lying within their best fits, losses at high currents are noticeable enough that using direct proportion to calculate battery capacity (eg. 500 mA for 2h equals 250 mA for 4h) is too erroneous to account for losses. I find this similar with trying to use Newton's physics when travelling near light speed. Newton's physics can hold true in ground-level physics, but there's much more to consider when variables are scaled up. Here, it's the exponentially increasing charge losses with current.

In other words, considering that 1.174 is too small of an exponent will be an underestimation. Say, as of today, an iPhone 5S with a battery capacity of 1560 mAh provides 250 hours of standby and 10 hours of talking time.[12] This means 1560/250=6.24 mA of current draft during standby and 1560/10 = 156 mA during a voice call. Assume a 20 hour rated discharge, and the ratio of expected runtime to rated runtime in idle mode is around 19, whereas the same ratio is 0.44. The ratio of these two ratios is 44.

$$\frac{t}{H} = \left(\frac{1560}{6.24 \times 20}\right)^{1.174} = 19.40$$

$$\frac{t}{H} = \left(\frac{1560}{156 \times 20}\right)^{1.174} = 0.443$$

$$19.40 \div 0.443 = 44$$

In other words, with a “k” value of 1.174, talking on the phone compared to doing nothing would drain the battery 44 times faster, instead of the rated 25 times (250 hours standby/10 hours call).

Although the calculations above are based on mere assumptions, while lithium-ion batteries (used in smartphones) are known to have lower k values, the implications of an exponential loss remain.

It’s seen that, Peukert’s Law causes significant charge losses even at seemingly low constants. It’s understandable how battery companies refrain from providing Peukert’s numbers for their batteries, for it’s not appealing to admit to an inability to provide a constant capacity at all times. But Peukert’s Law proves that capacity ratings can be misleading at high currents, and a battery with a lower Peukert number, despite a lower capacity will be more favorable in such cases. Thus, Peukert’s Law needs to be utilized whenever battery runtime matters.

Relevant/possible error sources:

A possible error source that was observed during changing batteries is the varying cable contact surface. While changing the batteries, physical contact with the battery holders changed the current reading on LabQuest. Applying pressure to the sides of the battery holder where the cables are in junction with the holder increased the current readings. The poor contact could have caused additional resistance, recalling from Physics classes that a cylindrical cable’s resistance is inversely proportional to its cross-sectional area.

Possible solutions are to a) use a standardized circuit board specialized for battery testing. b) use a battery testing chamber c) solder every junction point.

Another problem that was observed is that the batteries produced heat at high current drafts. Although room temperature is a constant, there is no way to control internal heat for the battery. Studies have proven that rechargeable batteries lose capacity when operating in heat, because chemically, the unwanted reactions that diminish the battery capacity and cause self-discharge are exclusively endothermic.[16] One may think that Graph 3.3 would display a trend with a significant slope if the effect was not negligible, for high currents should have diminished the charge capacity, but Figure 4.3 shows that temperature diminishes the battery capacity over many charge-discharge cycles (200-1000 cycles), which was beyond the scope of this experiment, as the number of cycles any battery was exposed to was less than three digits. The figures on the next page explain the phenomenon. Especially Figure 4C shows how drop rates in capacity are insignificant until 250 cycles.

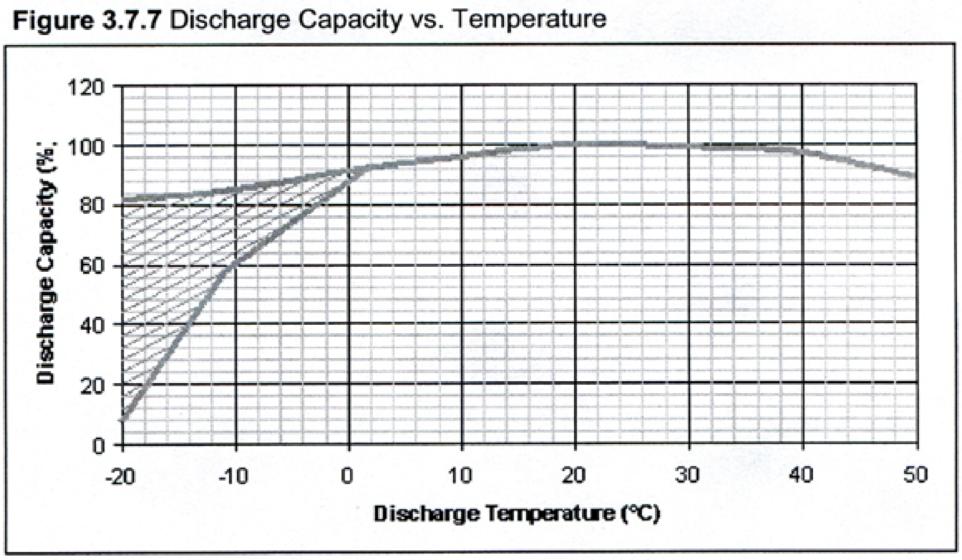

Figure 4.2: Available capacity of a NiMH battery through a temperature gradient.[14]

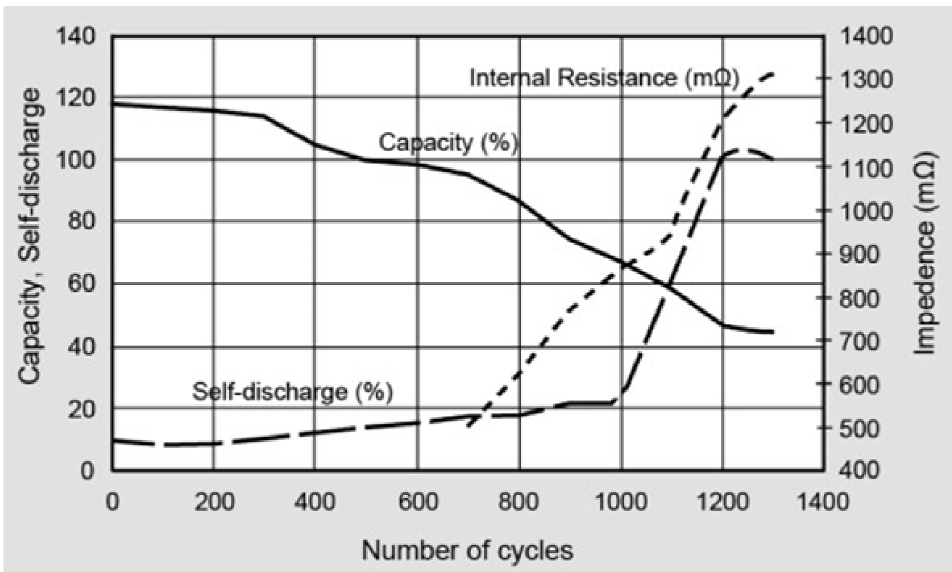

Figure 4.3: Capacity loss, internal resistance increase and self-discharge increase of NiMH batteries by increasing number of charge-discharge cycles. [15]

Even with a proper cooling mechanism, there's no way to stabilize the internal battery temperature, because there's no proper way of measuring the internal temperature, even with a laser thermometer, because a laser thermometer would measure the battery surface temperature. Therefore, it's best to conduct a separate study on the effects of temperature on GP 2700 series batteries. Although a similar experiment appears to be already done in Figure 4.2, the current rates that result in the graphed capacity values, which are needed to apply Peukert's Law, were unavailable in the article. Once such a comprehensive study is conducted and the results are out, the possible capacity loss and the proper correction calculation by temperature could be applied to Peukert's model to use the data in this article for reevaluation, mentioning again that the ambient temperature of this experiment was $(27 \pm 2)^{\circ}C$.

Another point of view to this issue is to leave the high temperature problem be. To have full real-life applicability, it's not necessary to stabilize the temperature factor. Because in real life, many portable devices heat when they work overtime (eg. smartphone gaming). Given that high temperatures are a natural result of high current drafts, the data collected should represent the real life situation by creating real life conditions, and as of today, smartphones don't have cooling fans, but automatically shut down instead if the temperature is critical.

Last, the current range of the experiment was kept too narrow can be a systematic error source. For a healthy correlation to be made, it'd be better to have data points keep a constant distance between each other, and to experiment at higher currents for lower percentage errors. To make that possible, it might be more convenient to work with one battery at a time and change resistances at different trials instead, because parallel connection of batteries changes current draft per battery in a non-linear fashion (ie. the decrease in current is decreasing [not constant] by increasing number of batteries). Using one battery might entail considering internal resistance as an error source, but still then, it's too small to have a significant effect on the end results as explained.

The experiment's implications are not limited to smartphones; it engenders all portable devices. It also shows the importance of demanding smaller amounts of current for longer battery life. Decreasing screen brightness, preferring 2G mobile networks over 3G/4G, disabling unused wireless connectivity altogether and underclocking (slowing down) the processor are only some of the means of saving energy by demanding less current. It also shows that these energy saving tips will not only reduce energy use, but will also make more battery capacity available to the user. Therefore, by keeping Peukert's Law in mind, the battery life will improve in both ways.

Bibliography

[1] Sony's commercialization of Li-ionbatteries in 1991.
http://cen.acs.org/articles/92/i17/Patent-Picks-Lithium-Ion-Batteries.html

[2] C-rate explained.
http://web.mit.edu/evt/summary$_{b}attery_{s}pecifications.pdf$
$Accessedon$26.2.2015.

[3] Ohm's Law
Robert A. Millikan and E. S. Bishop (1917). Elements of Electricity. American Technical Society. p. 54.

[4] The Joule effect
Crew, Henry (1910). General physics: an elementary text-book for colleges, 2nd Edition. The University of Michigan: The Macmillan Company. pp. 402–404.

[5] The Peukert effect
http://www.evdl.org/pages/hartpeukert.html

[6] The Peukert's Law in formula, and its limitations
http://all-about-lead-acid-batteries.capnfatz.com/all-about-lead-acid-batteries/lead-acid-battery-fundamentals/peukerts-law-and-exponent-explained/

[7] Self-discharge
Battery performance characteristics, MPower UK, 23 February 2007. Information on self-discharge characteristics of battery types.

[8] Battery's contents
http://www.omega.com/Msds/msdspdf/MSDS$_{0}404.pdf http : //www.fpbattery.com/ni_{m}h.htm$

[9] Image on voltage curves
http://www.voltmagic.com/faqs.htm

[10] Constants
http://batteryuniversity.com/learn/article/discharging$_{a}t_{h}igh_{a}nd_{l}ow_{t}emperatures$

[11] Method help
http://batteryuniversity.com/learn/article/how$_{t}o_{c}harge_{w}hen_{t}o_{c}harge_{t}able$

[12] iPhone's battery information
Klug, Brian (September 12, 2013). "Apple Increases iPhone 5C and 5S Battery Sizes relative to iPhone 5". AnandTech. Retrieved October 11, 2013.

[13] Literary value: Peukert coefficient between 1 and 1.2
http://www.union-services.com/aevs/1419-1423.pdf

[14] Discharge Capacity vs. Temperature image
http://en.globtek.com/nimh-battery-safety-notes/

[15] Extensive NiMH capacity loss, self-discharge and internal resistance image
http://batteryuniversity.com/learn/article/charging$_{n}ickel_{m}etal_{h}ydride$

[16] Endothermic unwanted reactions fact
http://batteryuniversity.com/learn/article/the$_{s}ecrets_{o}f_{b}attery_{r}untime$

(3961 words)