Testing and Analysis of FIRST® Robotics Batteries

Abstract

Objective:

This study aimed to develop an efficient, repeatable testing method for *FIRST* Robotics Batteries. The accumulation of batteries over time necessitates testing and ranking to determine the best batteries for use in competitions. Several testing standards from the industry were researched and considered in this study; those considered specifically relevant to *FIRST* Batteries were applied. Through this research, it was determined advantageous to test and rank battery performance with the use of an automated system which, eliminated human error.

Methods:

The "Battery Test Kiosk", a proprietary hardware device that varies the load on a battery while simultaneously sensing current and voltage, was successfully able to test a battery in less than ten seconds. Processing based high-level software was developed to communicate with the Battery Test Kiosk hardware and coordinate these tests. Moreover, the system could effectively simulate a *FIRST* Robotics Competition match on a battery. Included in the software was the ability for high level computations to analyze and graph the data received from the testing hardware. These tests were printed and logged for post analysis.

Results:

Twenty-eight batteries spanning five manufacturers, ranging in age up to nine years old, were characterized. Tested batteries were ranked based on maximum power output and internal resistance. The observed maximum power of the batteries ranged from 1100W to 524W and the internal resistance from 14.8mΩ to 35.0mΩ respectively. It was noted that the batteries exhibited a nonlinear trend with age and higher performance from some manufacturers. Ultimately, a strong correlation was shown between battery age and possible charge/discharge cycles.

Conclusion:

Through this study, it was shown that *FIRST* Robotics Battery performance can be consistently and accurately measured using a test instrument with automated software. Moreover, it was shown that batteries can undergo *FIRST* Robotics Competition match conditions without the need of a robot. This study reaffirmed the importance of a battery's age on performance, but also further confirms the importance of the number of charge/discharge cycles a battery undergoes. Since these cycles increase with age, improvements can be made by implementing RFID tags and a smartphone application for tracking. The availability of the Battery Test Kiosk project to the *FIRST* community enables teams to not only understand their own batteries more effectively, but to also enable the sharing of test data. This data results in further analysis across a wide spectrum of teams to gain a better understanding of how *FIRST* Batteries perform.

Table of Contents

Preface 5
Executive Summary 7
Introduction 9
FIRST Robotics Battery Demands and Performance 11
Testing Methodology 13
Testing Procedure 13
Battery Internal Resistance Measurement 16
Data Interpretation and Battery Ranking 17
Safety 21
Tools Used 23
Digital Battery Analyzer 23
Battery Test Kiosk 23
Battery Logger 26
Battery Charger 27
Battery Basics 29
Lead Acid Fundamentals 29
Charging and Discharging 30
Battery Modelling 31
Battery Capacity 32
FIRST Robotics Battery Specifications 33
Summary of Battery Standards Researched 35
Society of Automotive Engineers Surface Vehicle Standard *SAE-J240 [2]* 35
Society of Automotive Engineers Surface Vehicle Standard *SAE-J537 [3]* 35
Underwriters Laboratories Inc. Standard for Safety Household & Commercial Batteries *UL-2054 [10]*35
British Standard Lead-Acid Traction Batteries Methods of Test *BS EN 60254-1 [1]* 36
International Electrotechnical Commission - IEC 61982-3 Secondary Batteries for the Propulsion of Electric Road Vehicles [4] 36
Study Participants 37
References 39
Appendix I – Result Data 41
Appendix II – Standards Cover Pages 55
Appendix III – Glossary of Terms 59

Preface

In the 2014 competition season, our robot had a complete failure while on the field during a critical qualifying match. The team did an in-depth analysis of the failure and the cause was determined to be low battery voltage, which reset the robot's processor and shut all functions down. This was a surprising finding, as we were using a new battery that was checked before being placed in the robot.

This finding provided the incentive to pursue the following questions:

1. *How do we really know how our batteries will perform in a competition?*
2. *Are there industry standards for battery testing?*
3. *Can we perform regimented testing and rank our batteries?*
4. *What are the characteristics of the FIRST lead acid batteries and can we better understand how to measure them?*
5. *Can we create an automated battery test platform (hardware and software) that can characterize a battery under load as well as simulate a FIRST Robotics match?*

The challenges presented were initially met by the team using a test methodology that relied on repeated testing by dedicated battery testers (students). This battery report is a revision of a previous report that incorporated a manual method of testing. A new Battery Test Kiosk was developed to automate, streamline and bring consistency to testing FIRST batteries. The Battery Test Kiosk allows Team 2619 to have a reliable and repeatable battery test that can also be brought to competitions so that other teams may benefit from these findings. It is the team's intention to share this knowledge with other FIRST teams so that they may also accelerate their battery testing methods and learn about battery technology.

April 2018
FIRST Team 2619
"The Charge" – Robotics Team of Herbert Henry Dow High School
Midland Public Schools
Midland, MI USA
www.the-charge.com

A copy of this report can be downloaded from the website above.

Executive Summary

Every team has been there, the moment when your robot is performing great and suddenly your battery starts browning out. Over the years teams accumulate numerous batteries, including one in the kit of parts every year. However, the age of a battery is not always a guaranteed indication of performance. Without battery testing or ranking, a team has no idea which batteries are the best to use in competition. Although the fast and simplistic handheld battery testers seem like an appealing option, rigorous battery testing at different loads can accurately assess battery performance. Team 2619 has developed a completely automated battery testing system that increases repeatability and performance assessment to a significantly higher level.

Originally, Team 2619 tested batteries using a simple method. Batteries were connected to large resistors and their discharge was manually timed to a given level. This was then recorded and used to rank the batteries. However, this method was riddled with the possibility of human error, which inspired the idea for a more comprehensive battery testing system. First, research was done on industry standards in battery testing. This eventually led the team to design an automated "Battery Testing Kiosk" that incorporates hardware and software, eliminating human errors and bringing consistency in results. This compact system, not much bigger than a desktop computer, is able to test a battery under increasing load and produce a graph of its performance. Additionally, it is capable of simulating a robotics match, which allows teams to predict how their batteries would actually perform. This system is both efficient and effective. All of the data collected from this device is fully automated and unaffected by human error, allowing teams to create much more accurate battery assessments.

Using the "Battery Test Kiosk", teams can obtain battery rankings more accurately than a simple handheld device or ranking based on age. Although, the rankings from this device may show that the newest batteries are good, they are not necessarily the best a team has to offer. By implementing this quick and precise system, teams are able to thoroughly test all of their batteries and determine their most suitable batteries as well as monitor battery performance as the batteries age. For this reason, Team 2619 would like to make this device available to other teams that wish to build it as well. At a fairly low cost, teams can create the same system using our custom boards and the software program that accompanies the device. The "Battery Test Kiosk" has the potential to improve the battery rankings of any team that implements it.

Introduction

The battery is the primary energy source for the robot. It is therefore critical that the robot uses the best battery available when entering the competition field. Many FIRST teams learn about the importance of a battery in the worst possible way, with a poorly performing robot or even a total failure during a match. A poorly performing battery may not only impede the speed and maneuverability of a robot, but can also cause failure of the control system if the battery voltage falls below a critical threshold.

FIRST robotics teams acquire batteries through successive competition seasons, and by procuring batteries on their own. Over time, teams may have many more batteries than is practical to bring to competitions. Since batteries are bulky, heavy and generally difficult to transport, it is important to only bring the best batteries to the competition. This is especially true when teams have a large quantity (even dozens) of batteries.

Figure 1 – Some of the Batteries Aquired by Team 2619

The question at hand is how to rate a battery's performance using both static and dynamic testing parameters. Ideally, each battery would be placed in a robot and run through a competition with its performance being simultaneously measured and recorded. This data would then be post processed and compared to other batteries. Unfortunately, the following variables are difficult to control:

- How can individual batteries be compared to one another using a "competition-like" test without assuring that the test not only mimic a real competition, but be absolutely repeatable? This would be critical to providing a scientific and engineered analysis of each battery's performance using a scenario that is virtually identical to a competitive match.

- Classification of batteries simply due to their date of purchase is a poor decision making criteria. Battery performance is not simply age related. It depends on charge/discharge cycles, depth of discharges, vibration, temperature and host of other parameters that are difficult to track over the life of the battery.

The purpose of this study is to eliminate the variations of battery testing by applying testing benchmarks that have roots in industry standards. Each battery will be tested in accordance to strict guidelines to eliminate the possibility of introducing variability in the results. The analysis of the data will then be presented and the batteries will be ranked from the best to worst performing.

FIRST Robotics Battery Demands and Performance

Before commencing a suite of tests on FIRST batteries, it would be beneficial to understand what the battery experiences in terms of the loading placed upon it by the robot during a match. In the 2014 season, the robot's processor logged the battery voltage during a match, which made it possible for a post-processed analysis. This was the mechanism used in determining a battery failure by Team 2619 during a critical elimination match that year. Unfortunately, the battery's current consumption was beyond the capability of the processor logs, which leaves a major void in the post-analysis process. To fully understand the power delivered by a battery (i.e. the demand placed on it), both current and voltage is necessary, as power is current multiplied by voltage. A means is necessary to log both the battery voltage and current while the robot is in action in a competitive environment.

The device used to log this data was constructed and tested during the fall of 2014 at the FIRST of the Great Lakes Bay Region off season competition called the "Bot-Bash". This "battery logger" instrument provided the team details of what a FIRST battery must deliver during a match (refer to Figure 2). Details about the battery logger are provided in the "Tools Used" section of this report.

The logged battery demand graph reveals several interesting points:

- As expected, during the quiescent period before the match begins, the battery delivers a small amount of current to keep the processor operating while the match is being set up. This may seem insignificant, but due to the variability of field configuration before a match, this could potentially be a long period of time which the battery needs to deliver a lower current.

- The autonomous period is rather small in comparison to the tele-operated period. However, there is a significant spike of current that signals the beginning of the autonomous period.

- The tele-operated period is responsible for the most demand placed on the battery. It is comprised with what seems like a series of "spikes" of current and "sags" of voltage. As the driver pushes the controls and the drivetrain responds, a huge spike of current is required. This can be exacerbated by the other motors actuating various devices on the robot. Nonetheless, it is interesting to see that the motor current is far from constant during this timeframe.

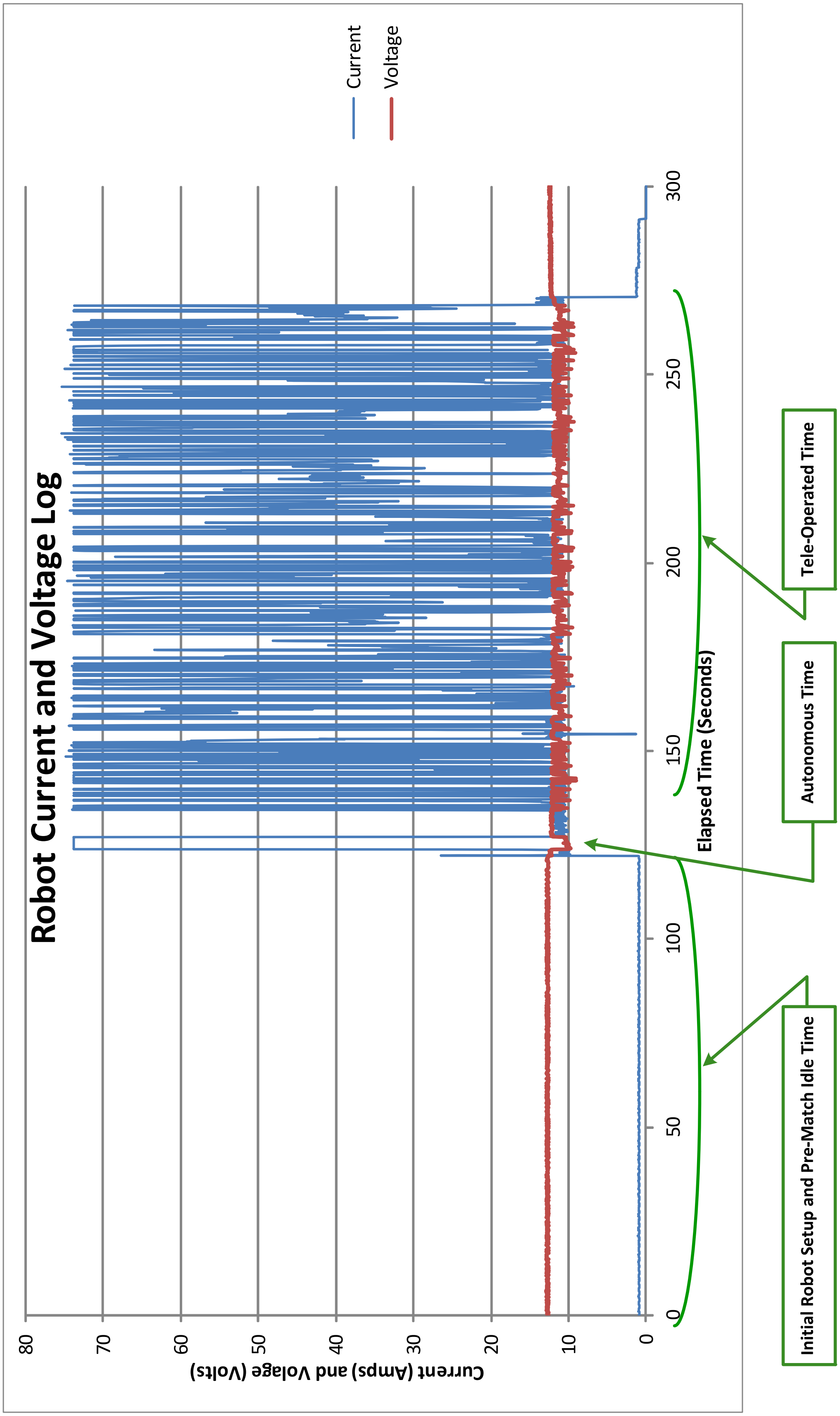


Figure 2 – Robot Voltage and Current Log During a Competition

Testing Methodology

Batteries are tested using a dynamic load which provides a graph of Voltage vs. Current. The Battery Test Kiosk device, which is described in greater detail later, can vary the load on the battery from zero to 125 Amps, while simultaneously recording the voltage. Ohm's law states that the slope of this graph is the battery's internal resistance. Interestingly enough, the slope is not necessarily constant, i.e. the plot is not necessarily linear. This revelation is surprising, as hand-held internal resistance instruments provide only a singular number with regards to internal resistance.

A battery must provide ample high current when it is demanded by the load, as well as a prolonged low current over a period of time. The life of a battery is often tied to a function of the number of charge and discharge cycles, as well as the depth of discharge it has experienced. A battery's internal resistance has a strong correlation to battery life and is an important parameter which can be tested. Finally, a recipe based cycle test is needed to mimic a FIRST robotics match. This 'recipe' will have periods of high current and low current demands, as the robot accelerates and actuates its various systems.

Testing Procedure

Figure 3 summarizes the testing procedure that was followed for all the batteries tested. All batteries are charged using a Dual Pro RS3 battery charger from DeltaVolt. After which, the charge is verified at a minimum of 100% using a 'Battery Beak' from Cross The Road Electronics. The batteries are then "soaked" for 30 minutes, disconnected from the charger and quarantined. After soak, the batteries are dynamically loaded, with their initial characteristics graphed. The batteries are then subjected to a two minute simulated FIRST Robotics match that includes both autonomous and tele-operated periods. At the conclusion of the simulated match, the batteries are dynamically loaded again and a second line is added to the graph to depict a "before and after" characteristic.

Batteries subjected to high and low current demands react differently internally. High currents can cause internal heating which can affect a battery's internal resistance adversely. While researching industry standards, outlines for high and low current testing were found in IEC standard 60254-1 section 5 [1] and SAE-J240 revision 2002-10 section 3.4 [2], respectively. Battery discharge rates are non-linear and based on loading. This may be counterintuitive, but it is documented in the standard SAE J537 [3] as shown in Figure 4.

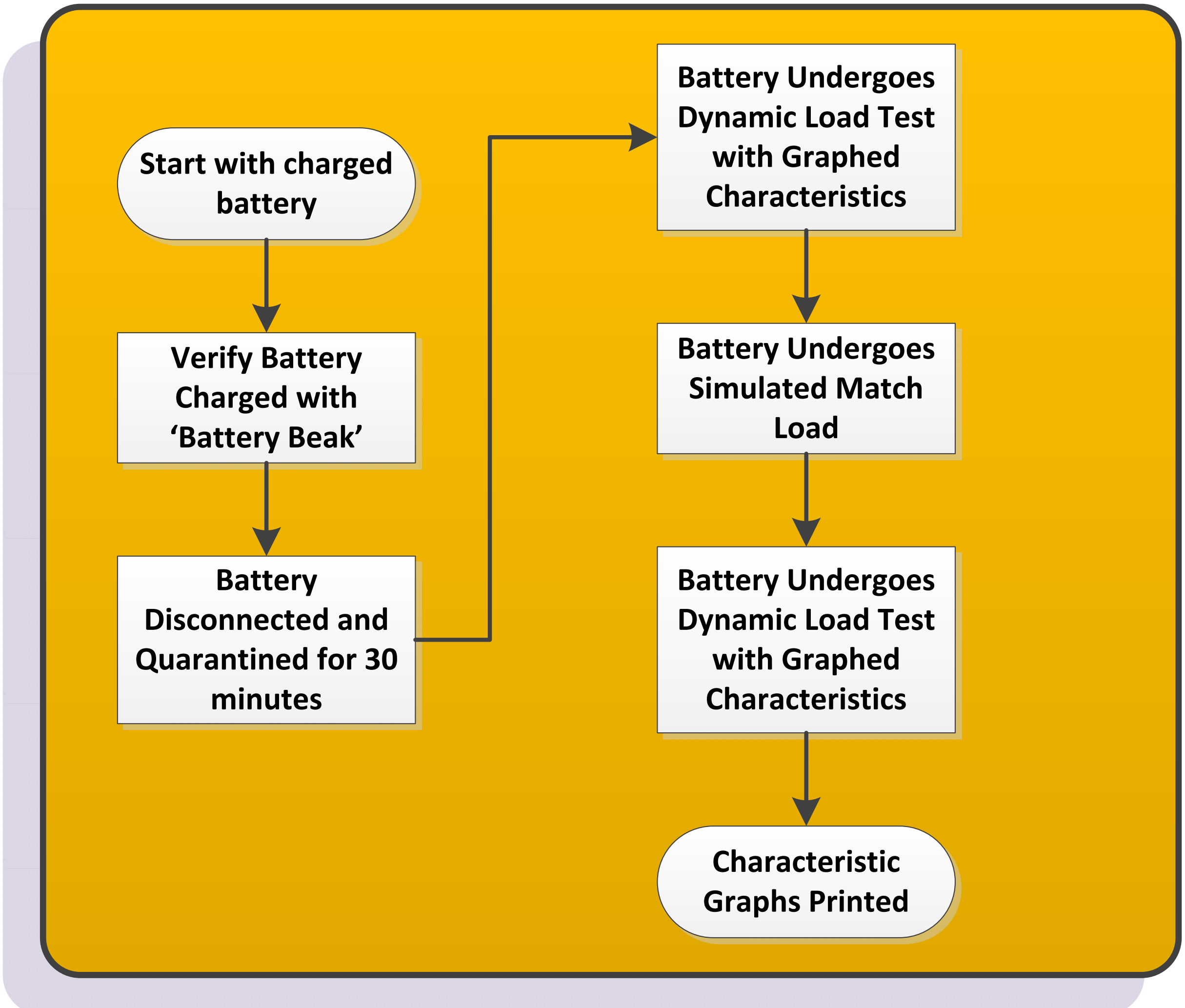


Figure 3 – Summary of Battery Testing Flowchart.

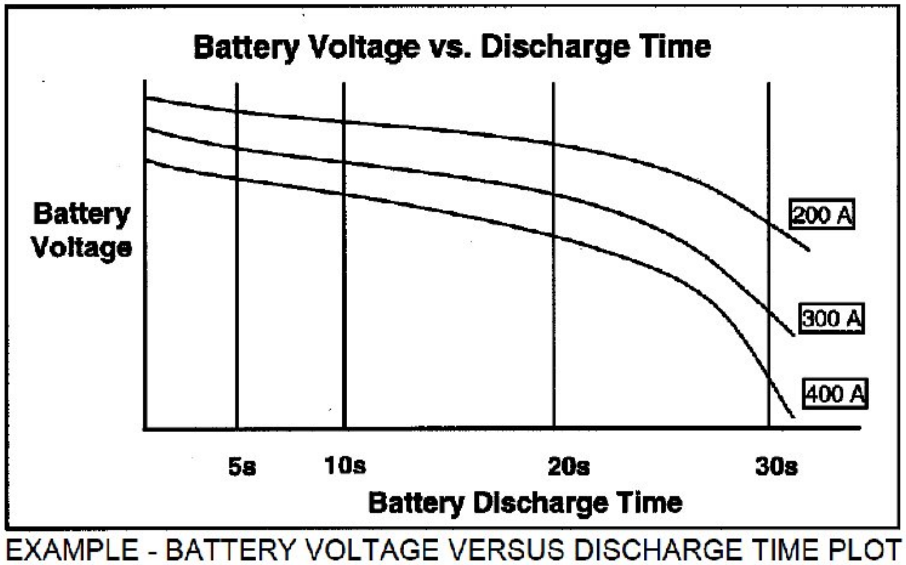


Figure 4 – SAE J537 [3] Depiction of battery discharge curves displaying non-linearity between various loads over time.

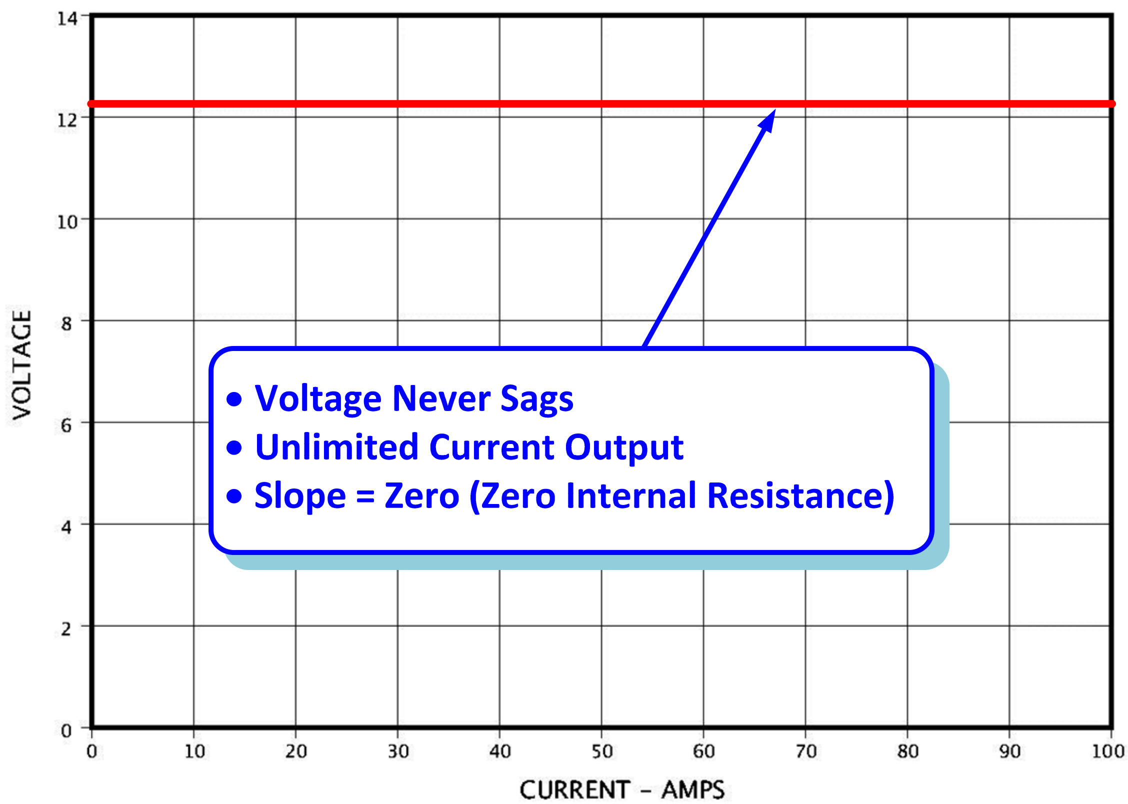


Figure 5 – Depiction of a "Perfect" Battery Characteristic Graph

The depiction of a "perfect" battery characteristic in Figure 5 shows that regardless of load on the battery, a constant output voltage is produced. This ideal characteristic is in contrast with a real battery, which has internal resistance. This non-zero internal resistance can be inferred by the slope of the characteristic line [4]. Note that the ideal battery has a slope of zero, which indicates an absence of internal resistance. An example of a "real" battery profile is shown in Figure 6.

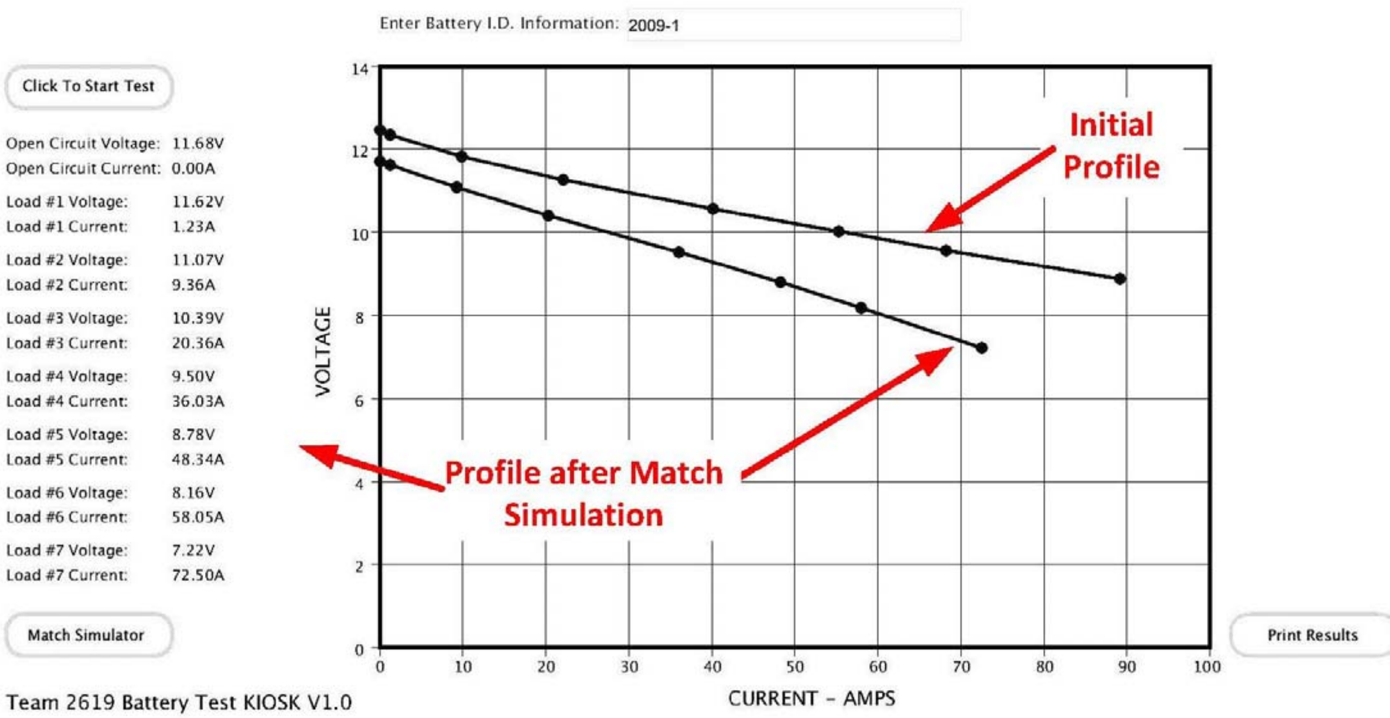


Figure 6 – Typical Battery Test Kiosk Characteristic Curve Output

Battery Internal Resistance Measurement

The parametric measurement of battery internal resistance was inferred in the slope of the battery's characteristic graph(s) – both before and after the match simulated load test. Internal heating of the battery skews the results of the internal resistance measurement, which occurs at higher load currents. Higher internal resistance is an indication of increased sulfation of the battery plates. The more a battery has been charged and discharged over its life, the higher the magnitude of sulfation and therefore, internal resistance. A higher internal resistance impedes the ability of the battery to deliver a high current demand and maintain its proper output voltage.

Data Interpretation and Battery Ranking

Batteries were ranked in the following manner:

1. All batteries followed the testing procedure outlined in the flowchart of Figure 3, and printouts were made of each result.

2. An Excel spreadsheet was developed based on the critical parameter of the highest current delivered by the battery after the match load simulation. The corresponding voltage was also recorded for this maximum load, which provided the power delivery capability of the battery (Power = Current * Voltage).

3. The batteries were then ranked by power delivery based on the formula above and the internal resistance measurement. There was a strong correlation between rankings of output power and internal resistance – an outcome that confirms the characteristic graph's slope.

For the 28 batteries tested in this study, the highest output power recorded was 1098.5 Watts, and the lowest was 55.7 Watts. A strong correlation to the slope of the battery characteristic curve and the battery ranking was observed, which aligns with increased internal resistance. A spreadsheet of the findings is shown on the next page. All battery characteristic curves recorded are provided in Appendix I.

In addition, this study also compiled three additional bar graphs that depict a profile of output power (Figure 8), battery age (Figure 9) and battery manufacturer (Figure 10). It can be noted that the output power vs. battery age bar graph does not take into consideration the charge / discharge cycles of the individual batteries. It is implied that the older batteries have a higher number of charge and discharge cycles, which can affect a battery's output power capability. It would be advantageous to track the number of charge discharge cycles for an individual battery to track its impact over the course of its lifetime.

Battery ID	Manufacturer	Internal Res. Initial mΩ	Internal Res. Final mΩ	Internal Res. Rank	Final I_O	Final V_O	Final P_O (Watts)	Final P_O Rank	Average Rank
2017-9	Duracell DURA12-18NB	15.62	15.20	2	104.42	10.52	1098.5	1	1.5
2017-10	Duracell DURA12-18NB	14.86	14.80	1	103.76	10.43	1082.2	2	1.5
2017-7	Duracell DURA12-18NB	16.19	15.74	4	103.32	10.41	1075.6	3	3.5
2016-2	Power Patrol SLA1116	15.23	15.39	3	102.91	10.34	1064.1	5	4
2018-1	Genesis NP18-12B	17.47	17.23	5	102.31	10.29	1052.8	6	5.5
2017-3	Power Patrol SLA1116	17.95	18.15	9	103.35	10.38	1072.8	4	6.5
2016-3	Genesis NP18-12B	17.92	17.90	7	102.19	10.27	1049.5	7	7
2018-2	KEYO KT-12180 HRT GEL	19.94	18.14	8	101.40	10.19	1033.3	9	8.5
2017-2	Power Patrol SLA1116	18.21	19.74	13	101.46	10.21	1035.9	8	10.5
2014-2	MKPowered ES17-12	17.30	18.43	10	100.96	10.12	1021.7	11	10.5
2018-3	KEYO KT-12180 HRT GEL	17.70	17.74	6	100.21	10.07	1009.1	15	10.5
2017-5	Genesis NP18-12B	19.67	19.34	12	101.12	10.16	1027.4	10	11
2014-1	Genesis NP18-12B	19.52	18.85	11	100.49	10.10	1014.9	13	12
2017-4	Power Patrol SLA1116	19.11	19.89	15	100.62	10.07	1013.2	14	14.5
2017-6	KEYO KT-12180 HRT	19.77	21.20	18	100.62	10.10	1016.3	12	15
2017-8	KEYO KT-12180 HRT	19.70	19.76	14	99.92	10.00	999.2	17	15.5
2017-1	Power Patrol SLA1116	19.77	19.97	16	100.02	10.05	1005.2	16	16
2014-3	MKPowered ES17-12	22.02	20.86	17	97.35	9.74	948.2	19	18
2015-1	Genesis NP18-12B	22.60	21.53	20	98.45	9.89	973.7	18	19
2016-1	Power Patrol SLA1116	24.44	21.89	21	96.47	9.68	933.8	20	20.5
2014-4	MKPowered ES17-12	22.14	21.28	19	94.43	9.47	894.3	22	20.5
2015-3	Genesis NP18-12B	23.90	23.53	22	94.74	9.52	901.9	21	21.5
2015-2	Genesis NP18-12B	22.78	24.48	24	94.36	9.45	891.7	23	23.5
2013-3	Genesis NP18-12B	24.38	24.01	23	93.23	9.33	869.8	25	24
2012-4	MKPowered ES17-12	23.35	26.04	25	93.74	9.41	882.1	24	24.5
2012-1	Genesis NP18-12B	32.12	28.55	26	85.79	8.59	736.9	26	26
2009-1	MKPowered ES17-12	27.62	34.98	27	72.50	7.22	523.5	27	27
2010-2	MKPowered ES17-12	57.82	151.30	28	23.69	2.35	55.7	28	28

Figure 7 – Compiled Battery Rankings

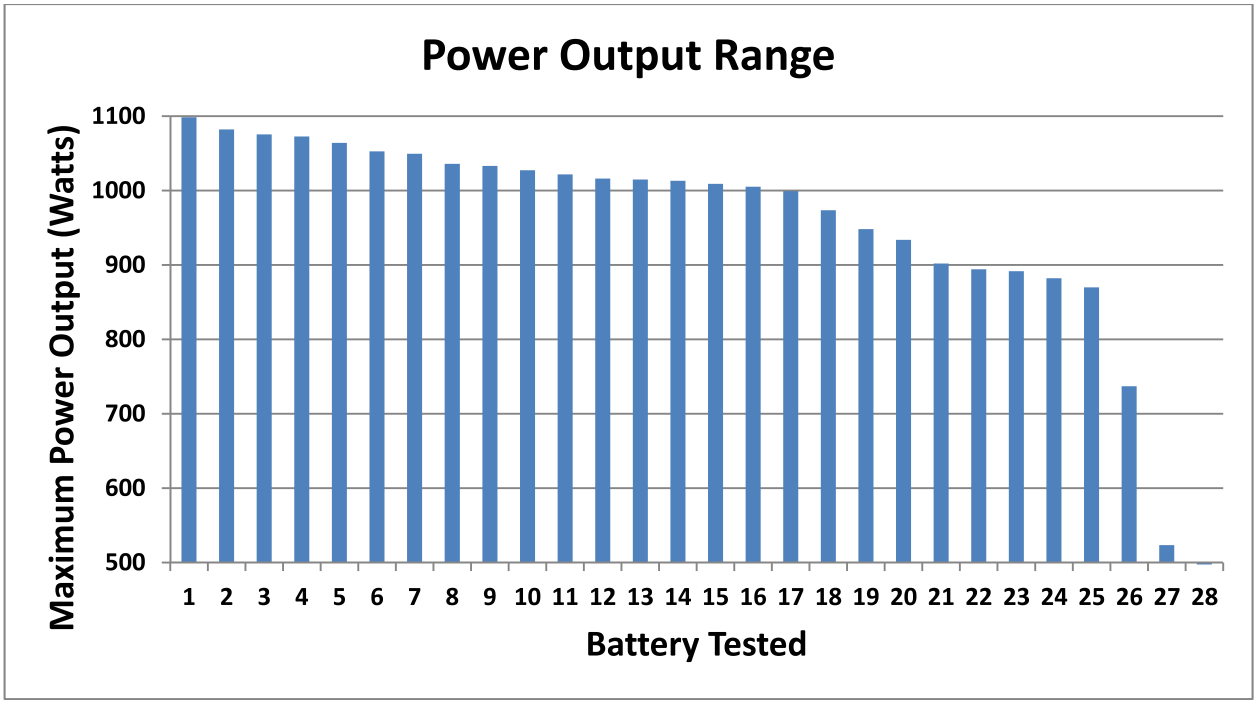


Figure 8 – Power Output Range Bar Graph

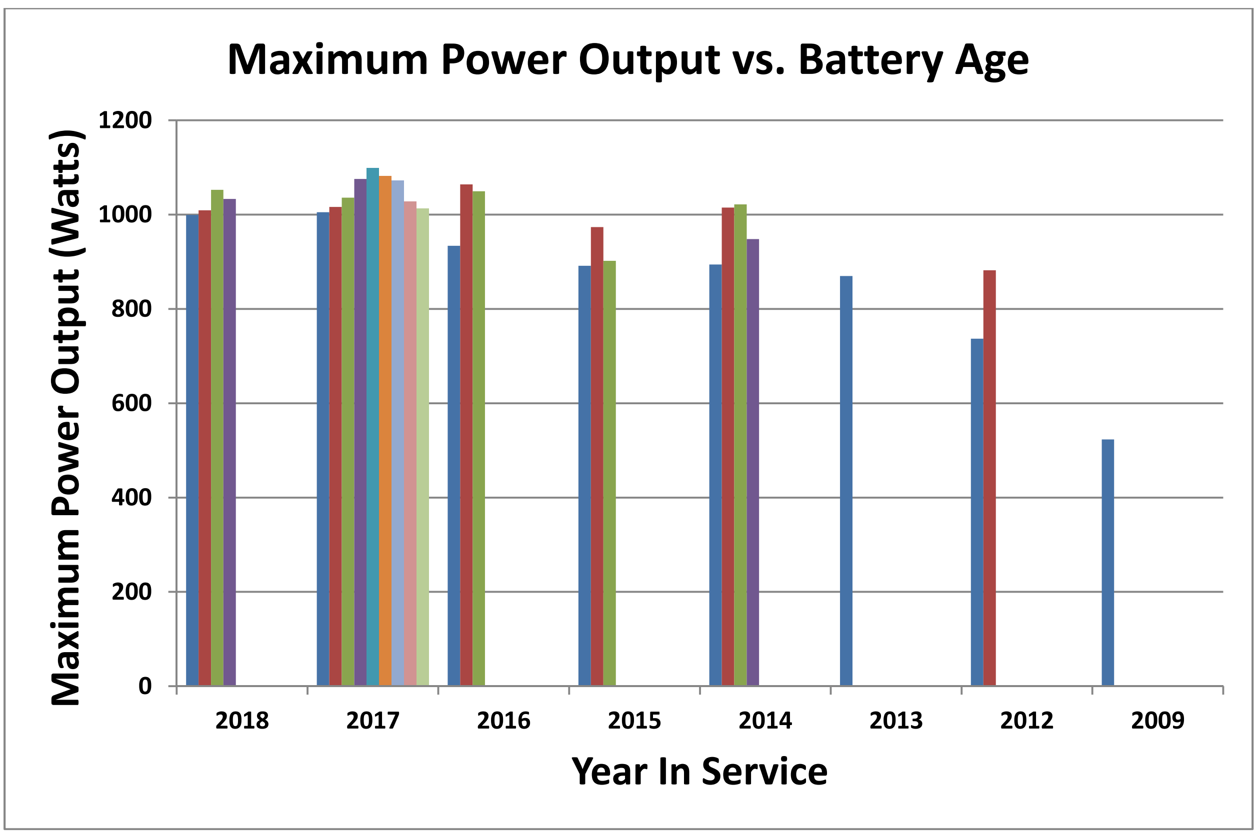


Figure 9 – Battery Age Bar Graph

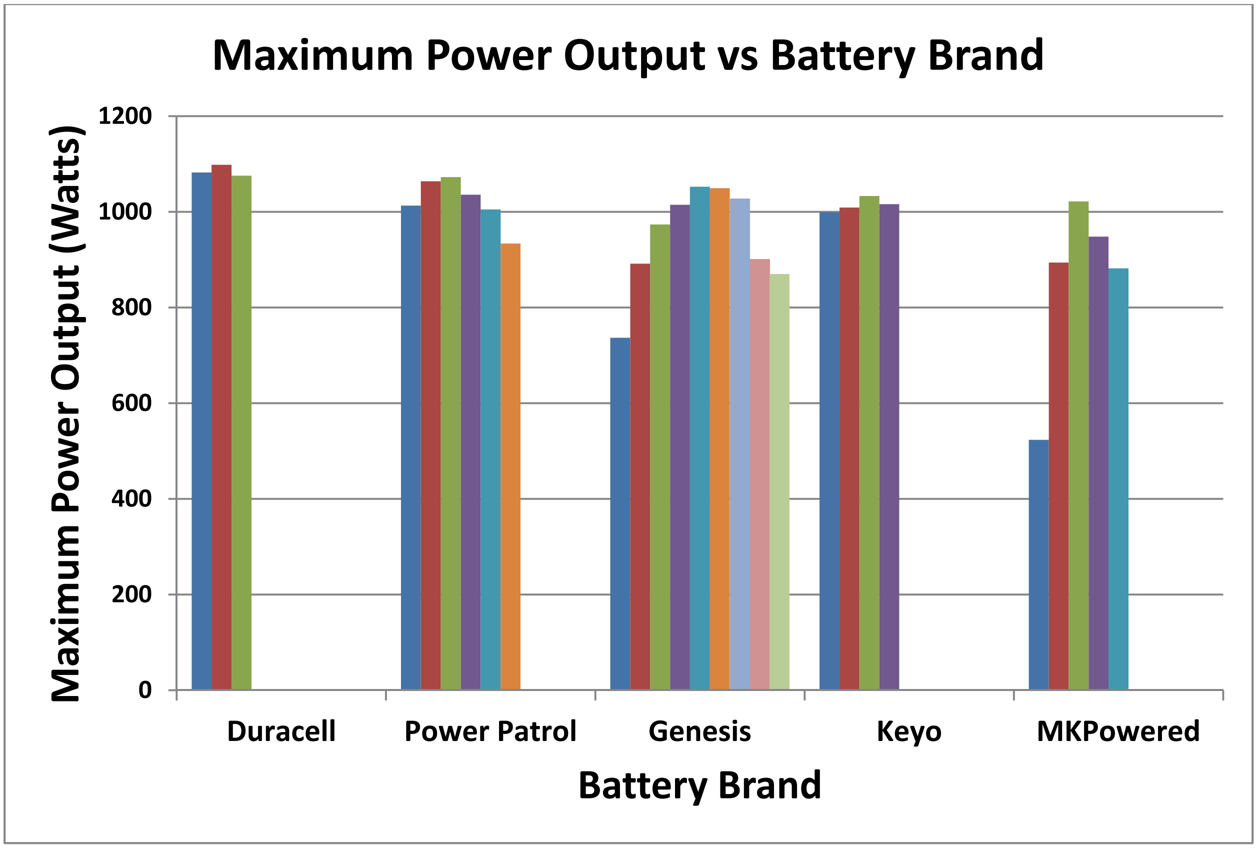


Figure 10 – Battery Brand Bar Graph

Safety

Working with sealed lead-acid batteries and discharge circuits must be done in a safe manner. During this study, Personal Protective Equipment (PPE) included safety glasses for all personnel involved. In addition, a FIRST-approved battery spill kit was on-hand for the unlikely event of a battery's case being compromised and spilling electrolyte. The Battery Test Kiosk's power load resistors are warm to the touch under use, but even after multiple tests, they do not constitute a burn risk. A fan was used to blow across the bank of power resistors to dissipate some of the heat generated by these resistors. There were no safety incidents during this study. Figure 11 shows students using the Battery Test Kiosk and following proper safety protocols.

Figure 11 – Students Testing Batteries.

Tools Used

The tools that were utilized for this study included off the shelf tools, modified tools and custom-built tools. These are outlined in the sections below:

Digital Battery Analyzer

A digital battery analyzer [9], as shown below was used to evaluate the battery's charge at the beginning and at the end of a test. The meter has a standard FIRST approved Power-Pole battery connector attached for ease of testing with FIRST batteries. Although this tester was not formally shown in the workflow flowchart (Figure 3), measurements were taken to initially correlate the slope of the line produced by the Battery Test Kiosk. The values from this analyzer were included in the data spreadsheet which is included in the appendix.

Figure 12 – Digital Battery Analyzer [9].

Battery Test Kiosk

The Battery Test Kiosk (Figure 14) is the heart of the battery test tools. Its purpose has three main thrusts:

- Provide a quick means to produce a battery performance characteristic profile with a wide range of load data and print out the results.

- Provide a means to simulate a FIRST Robotics match on any battery without burdening the team with actually installing a battery in a robot.

- Provide the ability to make testing batteries portable and able to be taken to competitions so that other FIRST teams can take advantage of this testing apparatus.

The Battery Test Kiosk incorporates a microcontroller based control system that communicates with a host PC via USB. The Kiosk can vary the load on a battery from zero to 125A while simultaneously measuring the current and the voltage. The acquired data is sent back to the host PC where a high level language (Processing 3.0) graphs the data in real time. The Battery Test Kiosk has a resolution of 4mV DC and 30mA DC. Its block diagram is depicted in Figure 13.

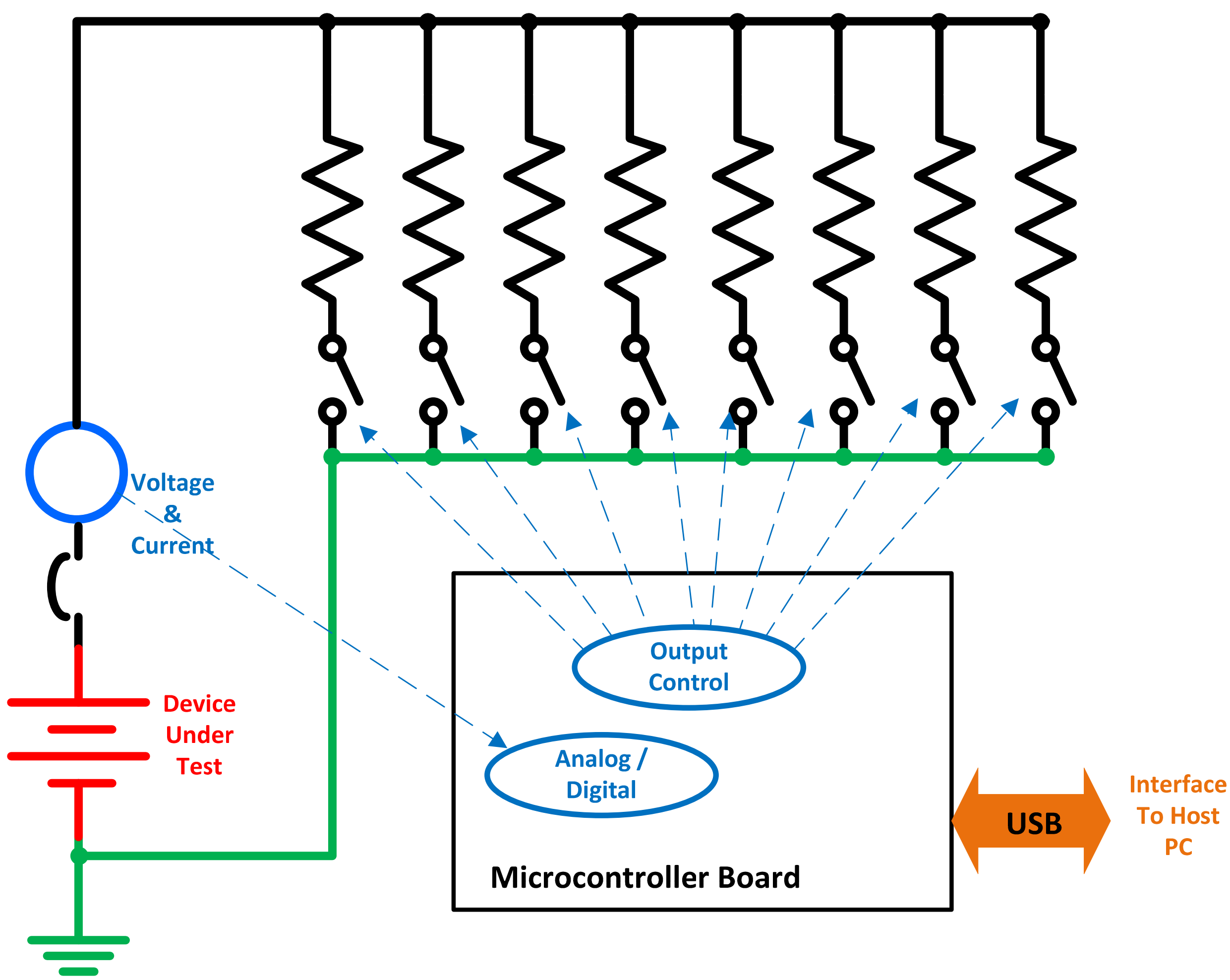


Figure 13 – Battery Test Kiosk Block Diagram

The Battery Test Kiosk was designed to interface with a host PC to upload data via a USB connection. The host PC runs custom high-level code in a programming language called "Processing 3.0", which is Java-like and has excellent graphics capabilities. It can also generate a pdf file of the output results, which is important in compiling data. A user friendly application was programmed so that any student could run battery tests with minimal training. A sample battery test's graphical output is shown in Figure 6.

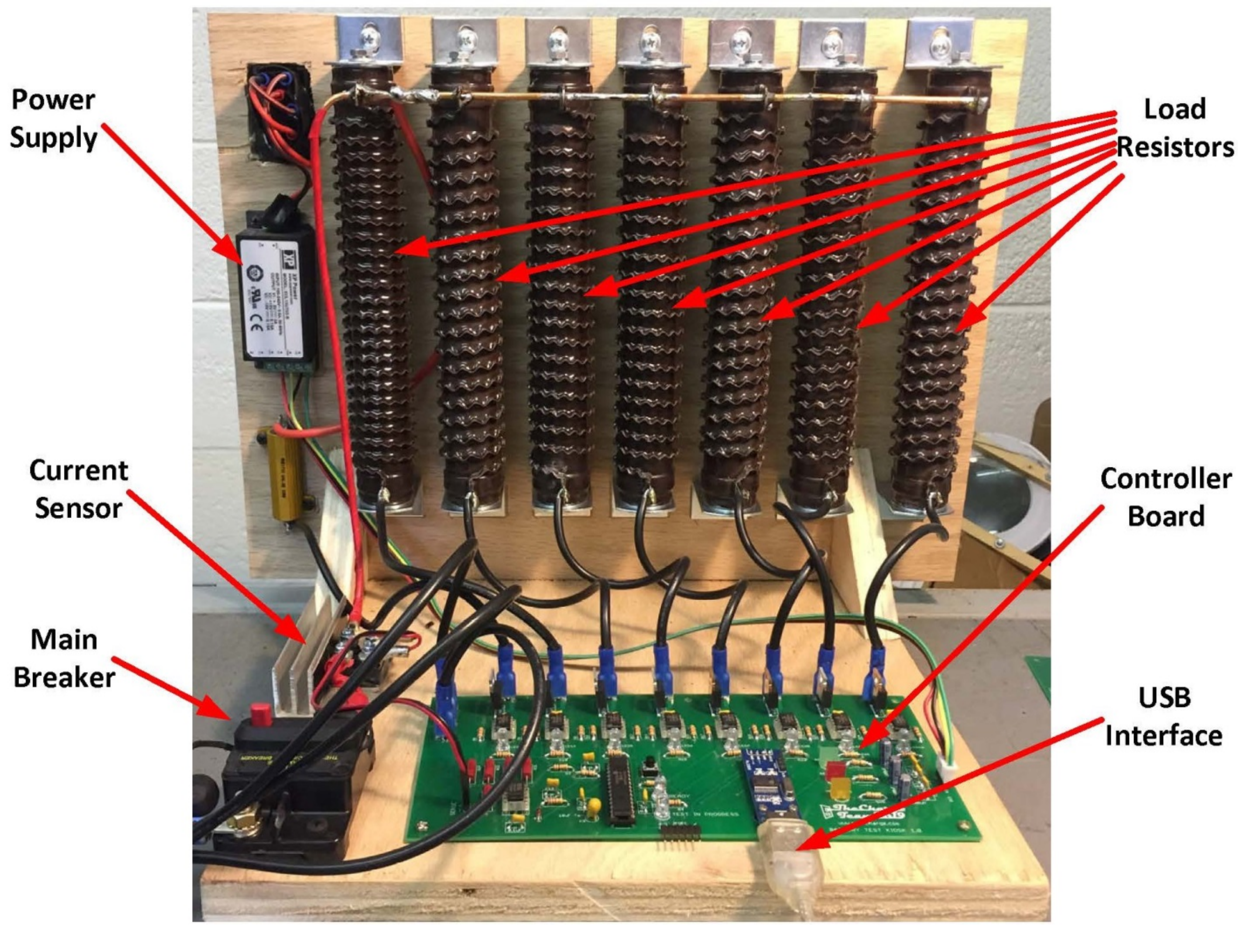


Figure 14 – Battery Test Kiosk Detail

The controller board's microcontroller directs eight high-current MOSFET switches that are connected to eight power load resistors. As these switches are turned on and off, a variable load is achieved, up to 125A if called upon. The MOSFETs themselves add negligible resistance, as they are rated at 1.25mΩ each, which is equivalent to approximately a one foot length of 12 AWG wire.

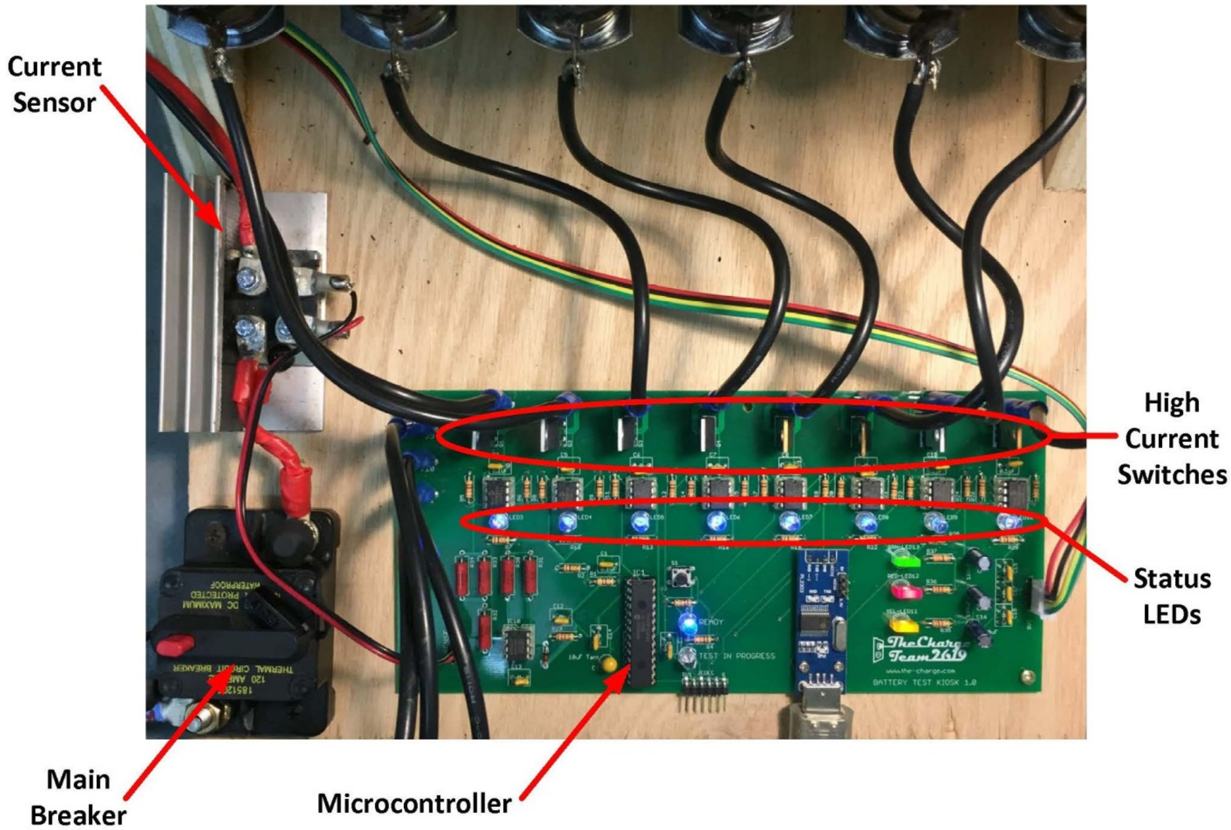


Figure 15 – Battery Test Kiosk Controller Board Detail

Battery Logger

The battery logger is a custom built instrument that is a self-powered data acquisition system that logs both current and voltage. It is meant to be portable and can be easily fitted inside a robot, between the battery and the robot proper. On command, it can log up to 10 minutes of voltage and current at 10 samples per second with a resolution of 10 bits (1 part in 1024). It is a useful tool to independently acquire battery voltage and current data while the robot is active. This data can be used for both battery performance analysis, as well as a better understanding of the demands placed on the battery by the robot while it is running.

The logger is self-powered and stores the acquired data in its own non-volatile memory. After acquisition is complete, the logger is then tethered to a host computer which uploads the stored data to an Excel spreadsheet. It incorporates an LCD display and pushbuttons for its user interface.

The battery logger's data was used to create a recipe based match simulation for the Battery Test Kiosk. Since each recipe test is identical, batteries can be compared with each other to ascertain performance using the acquired data. The main purpose of the match simulation is to provide the team a convenient method of stressing a battery without the need of a robot.

In this study, the battery logger was used on a real robot to log the dynamic load of the battery during a mock competition. This data was then used to create a recipe for the Battery Test Kiosk instrument, which was outlined previously.

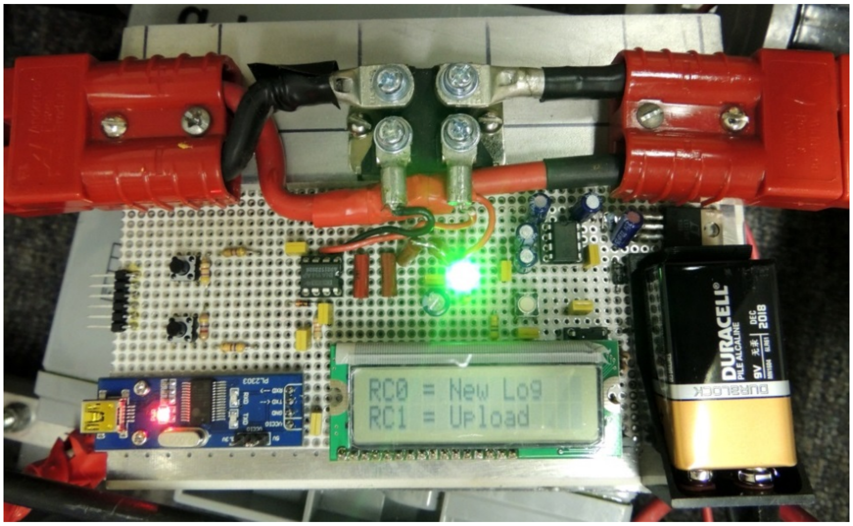


Figure 16 – Battery Logger

Battery Charger

The battery charger used in this study is the Dual Pro RS3 battery charger from DeltaVolt. This particular battery charger was found to comply with UL-2054 section 13.2 which pertains to the potential for overcurrent during charging. This particular standard states a "Limited Power Sources Test" [10] which requires limiting the output current of the charger to less than 8 Amps if the open circuit voltage of the battery is specified to be less than 20 Volts DC (which lead acid batteries have).

Team 2619 has designed and fabricated a rolling battery cart that consists of two of these chargers and six battery slots. This battery cart is used in competitions and provides a portable effective platform for the team. A picture of the battery cart is shown in Figure 17.

Figure 17 – Battery Cart, Top View

Battery Basics

A battery is a device that stores electrical energy. It is meant to be portable and provide power to a wide range of devices. Batteries can be rechargeable or non-rechargeable. The internal makeup and chemistry of a battery varies widely depending on the application, size, environment and cost. One of the oldest and most widely used battery types is the Lead Acid battery. It is the primary battery type used in non-electric and non-hybrid conventional automobiles. A sealed version of the Lead Acid battery is what is approved for use in FRC FIRST Robotics.

Lead Acid Fundamentals

The lead acid battery is comprised of a vessel that contains an aqueous electrolyte and two electrodes. The electrolyte is sulfuric acid; the negative electrode is porous lead, while the positive electrode is lead dioxide. The conduction mechanism within the electrolyte is facilitated by the migration of ions through drift and diffusion.

As charges migrate to their respective electrodes, this accumulation of charge limits further reaction, unless the charges are allowed to flow out of the cell. As the battery is discharged, additional sulfation of the electrodes occurs and acid electrolyte becomes weaker, lowering the terminal voltage. The conductivity of electrolyte and the contact resistance of sulfated electrodes contribute to internal resistance of battery [5].

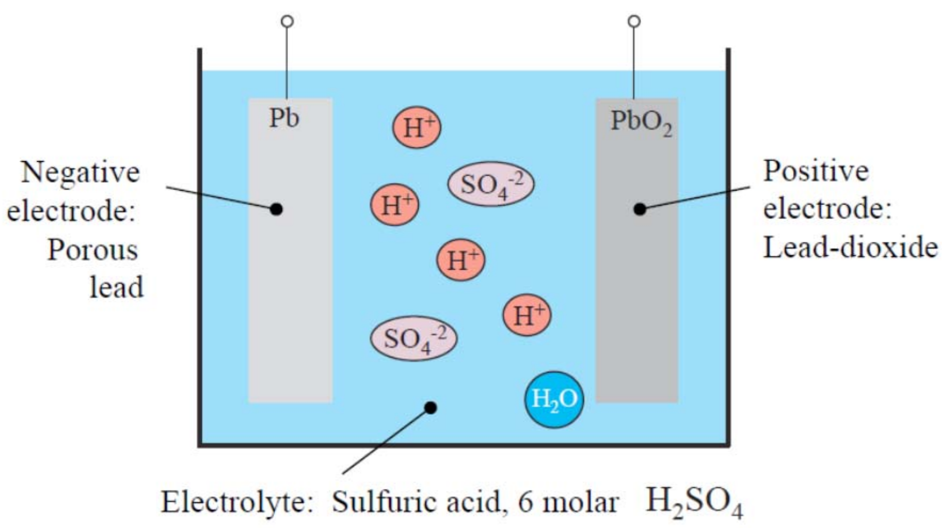


Figure 18 – Representation of a Lead Acid Cell [5].

A complete lead acid battery is comprised of six cells in series. Each cell has a nominal voltage of 2V and thus the fully charged lead acid battery has an open circuit voltage of 12V. The methodology of testing lead acid batteries will be heavily dependent on the individual cell voltage; as explained in the testing section of this study. The figure shown below depicts the complete 12V battery which is comprised of the individual cells in series.

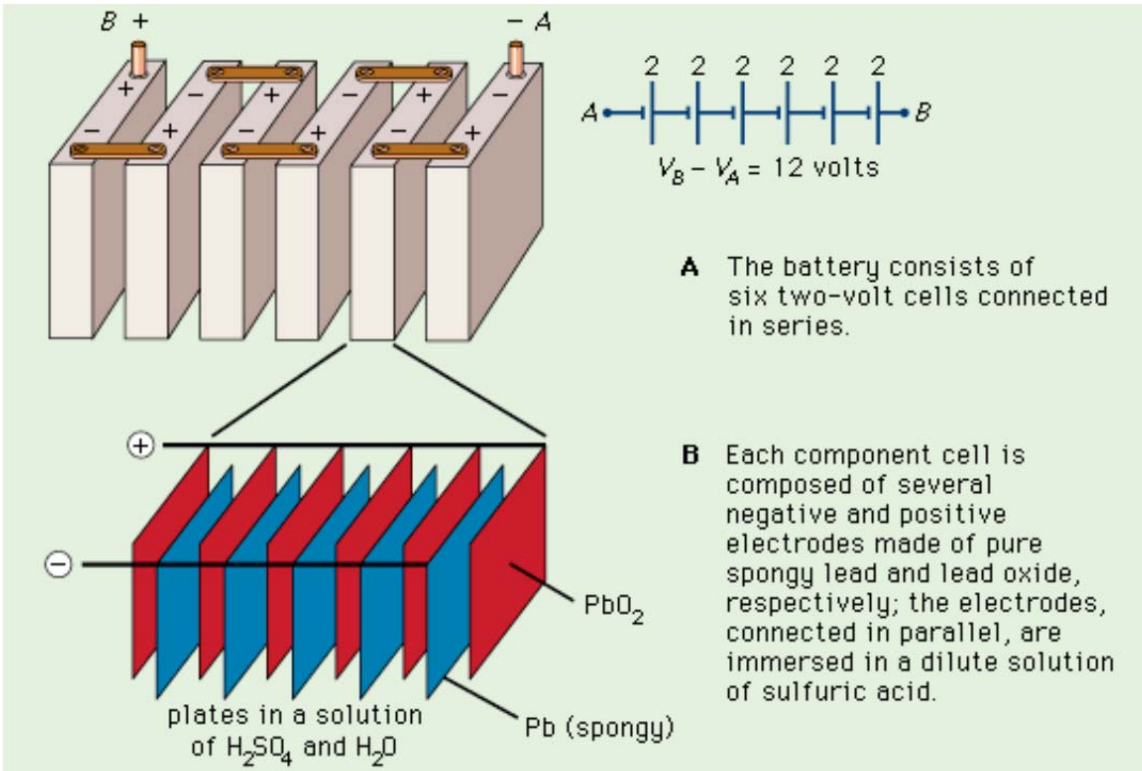


Figure 19 – Representation of a Lead Acid Battery [6].

Charging and Discharging

The flow of electrical current out of a battery's positive terminal through a load and back to the negative terminal is facilitated through the chemical reaction of the electrolyte and the plates of the battery. As charge is delivered to the load and the chemical reaction proceeds, sulfation develops on the battery plates driving up the internal resistance of the battery. The specific gravity of the electrolyte and its acidity decreases.

Charging the battery requires placing a voltage higher than the nominal cell voltage and driving electrical current into the positive terminal of the battery. This reverses the chemical reaction of discharge, increasing the specific gravity and the acidity of the electrolyte. Sulfation is also reversed on the battery plates.

Batteries also discharge over time when idle. This is known as self-discharge. The graph below depicts the typical self-discharge characteristics of lead acid storage batteries over a period of months.

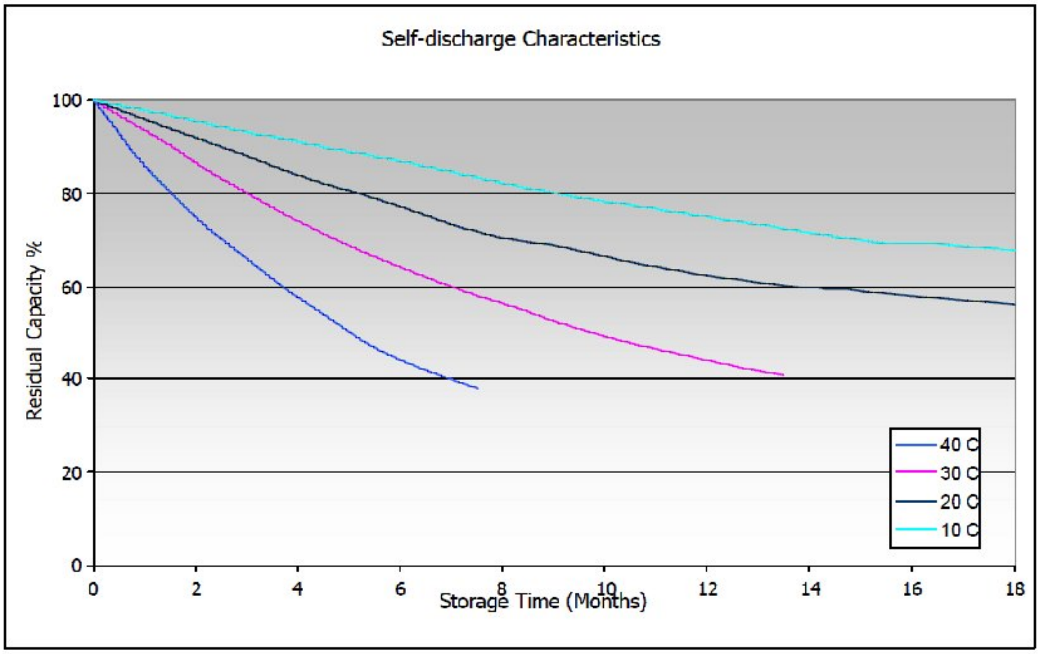


Figure 20 – Battery Self Discharge Characteristics [6].

Battery Modelling

The fundamental battery model from a circuit perspective is comprised of a battery with a series resistance. This series resistance is otherwise known as the "*internal resistance*" of the battery. Ideally, this resistance should be as close to zero as possible. In reality, this internal resistance varies for each battery, and is dependent on the battery's charge/discharge cycles, temperature, and chemical effects inside the electrodes (such as sulfation). The fully charged FIRST robotics battery at room temperature is specified to have an internal resistance of 11mΩ when new, at room temperature [7].

This internal resistance can be measured by placing a known resistor value between the battery terminals, then using Ohm's law to calculate the resistance. The hand-held battery analyzer used in this study measures the internal resistance with a push of a button. The battery cells and internal resistance circuit model is depicted in the figure on the next page:

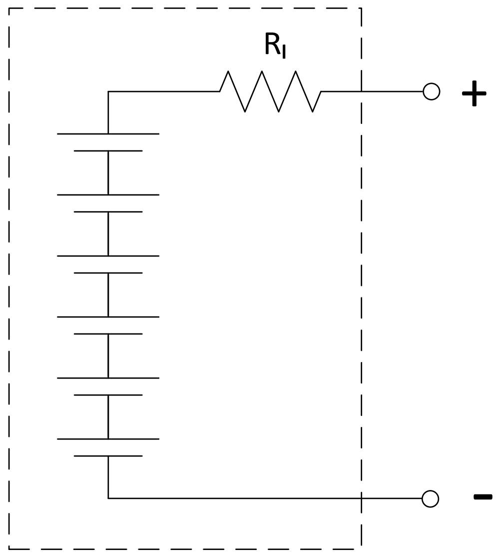


Figure 21 – Circuit Model of a Lead Acid Battery.

Battery Capacity

The capacity of a battery is a fundamental parameter that is specified as "C" in Ampere-Hours (Ah). The quantity C is defined as the current that discharges the battery in 1 hour, so that the battery capacity can be said to be C Ampere-hours.

If the battery is discharged more slowly, for example - at a current of C/10, then it would be expected that the battery would run longer (10 hours) before becoming discharged. However, in practice, the relationship between battery capacity and discharge current is not linear and less energy is recovered at faster discharge rates [5]. For this reason, both a high and low current discharge test was conducted in this study. The capacity of a battery can be modelled by Peukert's Equation, an empirical derivation that can be useful in calculating various discharge scenarios.

FIRST Robotics Battery Specifications

The FIRST robotics battery is specified as a 12V sealed rechargeable lead acid battery. It is available from two primary sources:

- Genesis / Yuasa NP18-12 (pictured below)
- MK ES17-12

Figure 22 – FIRST Robotics Typical Battery [7]

Specifications [7]:

- NOMINAL VOLTAGE: 12V
- NOMINAL CAPACITY:
  - 20 hr. rate of 0.86A to 10.5V 17.2Ah
  - 10 hr. rate of 1.6A to 10.5V 16.0Ah
  - 5 hr. rate of 2.9A to 10.2V 14.5Ah
  - 1 hr. rate of 10.3A to 9.60V 10.3Ah
- WEIGHT (approx.): 13.70 pounds (6.2 kgs.)
- ENERGY DENSITY (20 hr. rate): 1.47 WH/cubic inch (90 WH/liter)
- SPECIFIC ENERGY (20 hr. rate): 15.1 WH/pound (33.28 WH/kg)
- INTERNAL RESISTANCE OF CHARGED BATTERY: 11 milliohms (approx.)
- MAXIMUM DISCHARGE CURRENT WITH STANDARD TERMINALS: 150 amperes
- MAXIMUM SHORT-DURATION DISCHARGE CURRENT: 450 amperes
- OPERATING TEMPERATURE RANGE: CHARGE 5F to 122F (-15C to 50C)
  DISCHARGE -4F to 140F (-20C to 60C)

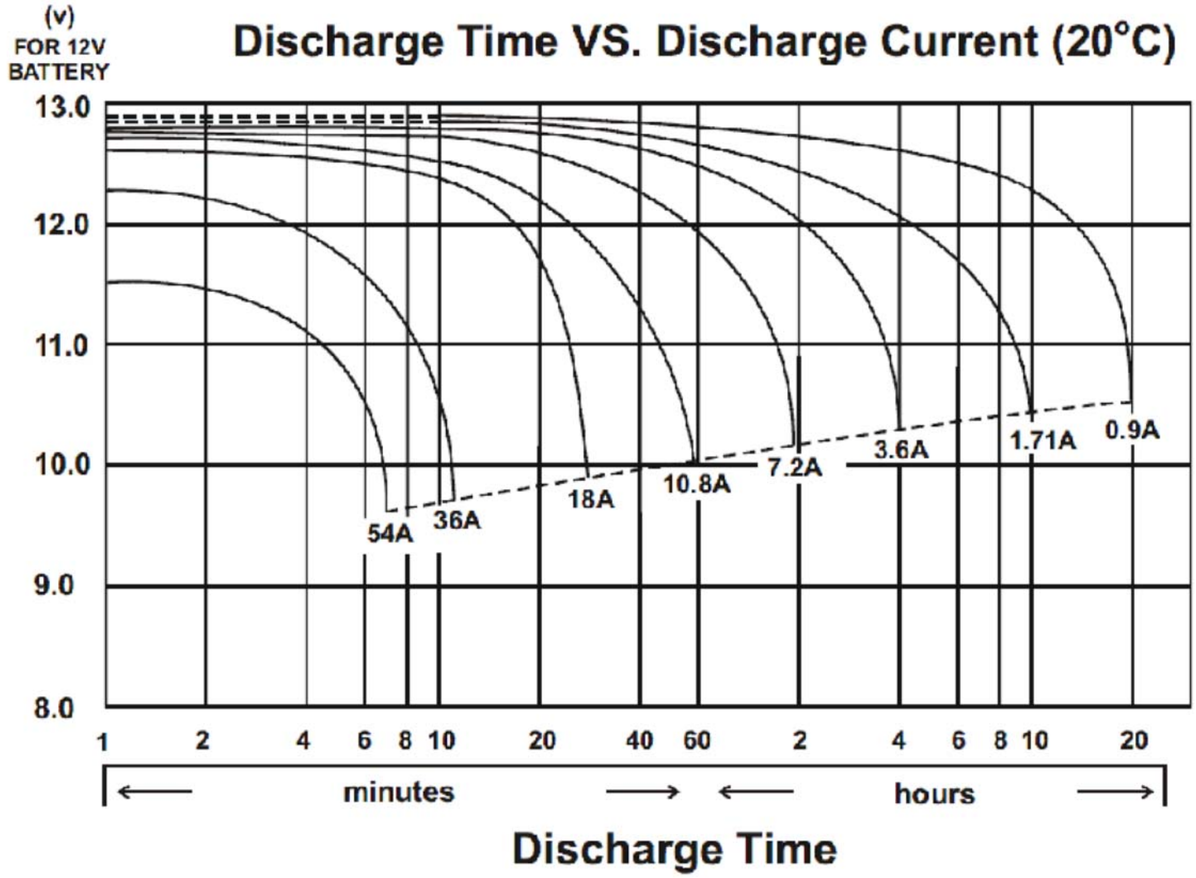


Figure 23 – MK ES17-12 Discharge Time vs. Discharge Current [8].

Summary of Battery Standards Researched

The following standards were researched by the team to better understand how the industry tests lead-acid batteries. These standards have varying degrees of applicability to this study, but the basic aim was to adopt the testing methodologies that most closely matched the batteries and conditions that FIRST Robotics batteries face by the teams that use them.

Society of Automotive Engineers Surface Vehicle Standard *SAE-J240 [2]*

SAE-J240 applies to automotive storage batteries that have a 180 minutes or less reserve capacity. Its purpose is to test the lifetime of a lead-acid battery by cycle testing them until they can no longer maintain a 1.2V / cell charge for a minimum of 30 seconds after it has been discharge cycled and then "soaked" at open circuit under a constant temperature for a period of 60 to 72 hours.

The cycling of battery charging and loading is a realistic test for FIRST batteries, as the frequency of cycling has a direct impact on battery life. However, the long soak period is unrealistic in testing the many batteries that FIRST teams may have. It is well suited to batteries that would be found in automobiles.

Society of Automotive Engineers Surface Vehicle Standard *SAE-J537 [3]*

SAE-J537 is a broad ranging standard that targets three specific areas of lead-acid battery testing. First, it specifies a procedure for charging batteries. It then has specifications for terminal geometry. Finally, it has a procedure of discharge rate. The discharge rate follows closely to SAE-J240, but specifically targeted to prevent internal gassing of Hydrogen to prevent explosions. These may be more applicable to non-sealed lead-acid batteries that have the capability of releasing gases from inside the battery.

The relevance to FIRST batteries can be found in two sections:

- Section: 3.5 (pp. 4) "Reserve Capacity Test" – *Battery discharge time under controlled conditions to a value of 10.5V.*
- Section: 3.6.5.2 (pp. 5) "Rechargeability" – *The percent ratio of the discharge time in minutes as obtained after a 120 minute recharge to the original reserve capacity value shall be at least 50%.*

Underwriters Laboratories Inc. Standard for Safety Household & Commercial Batteries *UL-2054 [10]*

UL-2054 is a comprehensive standard that is focused on Lithium batteries for household and commercial use. Although this would deviate from the lead-acid batteries used by FIRST teams, this standard nevertheless has many relevant and important considerations. It has a comprehensive glossary describing units of measure, terminology and components that are universal to all batteries. It also has an in-depth section on electrical testing which covers concepts such as "Performance Test Considerations (7), Short- Circuit (9) and Forced Discharge (12)" which can apply to any battery type.

The research team used this standard to better understand the concepts of battery test from UL, a corporation that has an influential presence at FIRST events, and even has a safety award that teams value.

British Standard Lead-Acid Traction Batteries Methods of Test *BS EN 60254-1 [1]*

This standard applies to what the British term as "Traction Batteries", or batteries in any type of device that utilizes traction from road vehicles to mechanical handling equipment such as autonomous guided vehicles (AGVs) or robots.

Its relevance to FIRST Robotics batteries is found in its testing procedures for:

- Capacity (5.2) – The ability of the battery to store energy.
- Charge Retention (5.3) – The ability to hold a charge for a period of time.
- Discharge Rate (5.4) – The ability to provide a large current based on demand.
- Cycle Endurance (5.5) – The number of charge and discharge cycles until a battery reaches a limit of 80% of capacity fully charged.

This standard especially highlights what FIRST Teams realize in battery life after many charge and discharge cycles under its section 5.5. This battery study confirms that the cycle endurance is a critical part of battery performance.

International Electrotechnical Commission - IEC 61982-3 Secondary Batteries for the Propulsion of Electric Road Vehicles [4]

This standard was referenced from the British Standard Lead-Acid Traction Batteries Methods of Test BS EN 60254-1. Research into this standard provided insight into the means for calculating the battery's internal resistance and maximum power output. This was outlined in section 5.2.6 of this document "*Determination of maximum power and battery resistance*" which had formulas and testing procedures.

Study Participants

Main Authors

Isabel Chaput **is currently a junior at H. H. Dow High School. She desires to pursue a degree in Biomedical Engineering at McGill University in the fall of 2019. Isabel has been a member of FIRST Team 2619 since 2015, serving as the first female leader of the electrical sub-team. She is also a member of National Honors Society, Model United Nations, Chemistry Club, and Alpine Club. In her free time, Isabel enjoys dancing, photography, horseback riding, and skiing.**

Michael Most **is currently a senior at H. H. Dow High School. He plans to pursue a degree in Electrical Engineering starting in the fall of 2018. Michael has been a member of FIRST Team 2619 since 2008 serving as numerous positions including Director and Electrical Lead. He has also been involved with the National Honor Society, DECA, and Lettuce Club. Michael enjoys playing his guitar, backpacking, skiing, and hunting.**

Robert Most **is a Professor of Electrical Engineering at Ferris State University, specializing in analog circuit design and signal processing. Authoring more than 15 papers and technical articles, Bob holds a BSEE from General Motors Institute (now Kettering) and an MSEE from Cornell University. In his spare time he volunteers for FIRST events, mentors students and enjoys backpacking.**

Proof-Readers

Steven Keptner	Student	***Josh Kline***	Student
Amelia Mylvaganam	Student	***Annalise Wohlford***	Student

Data Analysis and Compilation

Michael Most	Student	***Amelia Mylvaganam***	Student

Testing Participants

Isabel Chaput	Student	***Josh Kline***	Student
Michael Most	Student	***Amelia Mylvaganam***	Student
Robert Most	Mentor		

PowerPoint Presentation at FIRST World Championships, Detroit – April 26th 2018

Isabel Chaput	Student	***Michael Most***	Student
Robert Most	Mentor		

2015 Revision Contributors

Jill Poliskey	Student	***Satyajit Sarkar***	Student

References

[1] IEC 60254, "***Lead-acid traction batteries - General requirements and methods of test,***" British Standard BS EN 60254-1:2005, pp. 5, 9-10.

[2] SAE International, "***Surface Vehicle Standard J240,***" October 2002, pp. 1-2.

[3] SAE International, "***Surface Vehicle Standard J537,***" September 2000, pp. 6.

[4] IEC 61982-3, ***"Secondary batteries for the propulsion of electric road vehicles,"*** International Electrotechnical Commission, section 5.2.6.

[5] Robert York, "***Lead Acid Batteries***," Lecture Slides, University of California Santa Barbara, 2000, pp. 3-7, 23.

[6] The British Power Conversion Company, "***Technical Information British Standard 6290 Part 4,***" Hampshire, UK, 2006, pp. 19.

[7] ***NP18-12 Battery Datasheet***, www.enersys-emea.com/reserve/pdf/AS-NP-NPX-PS-002_0413.pdf

[8] ***ES17-12 Battery Datasheet***, www.mkbattery.com/images/ES17-12.pdf

[9] Cen-Tech – model #66892 **Digital Battery Analyzer**
http://www.harborfreight.com/digital-automotive-battery-analyzer-66892.html

[10]Underwriters Laboratories, "***UL-2054 Household and Commercial Batteries,***" Northbrook, Illinois, August 12, 2008, pp. 15.

[11] C&D Technologies, "***Lead Acid Battery Terminology,***" Blue Bell, Pennsylvania, 2012, pp. 2-21.

[12] Michael Weighall, "***Battery Test Guide***," Norwalk, Connecticut: *Digatron Firing Circuits Publication*, First Edition, 2000, pp. 15-28.

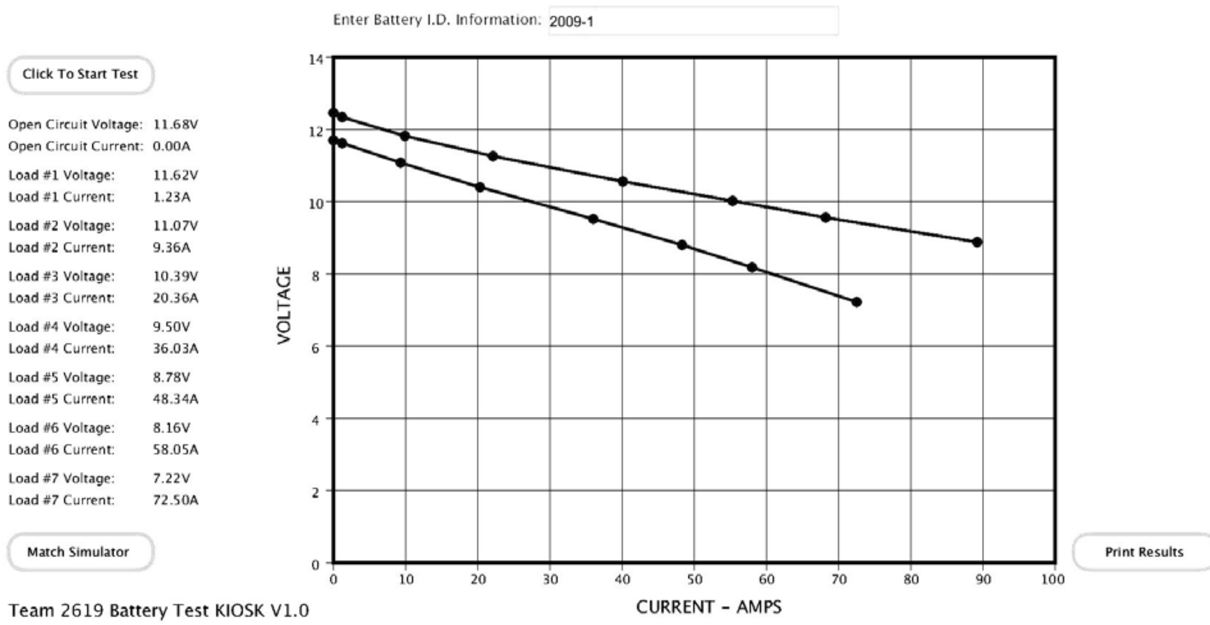
[13] Massachusetts Institute of Technology, "***A Guide to Understanding Battery Specifications,***" MIT Electric Vehicle Team, December 2008, pp. 1-2.

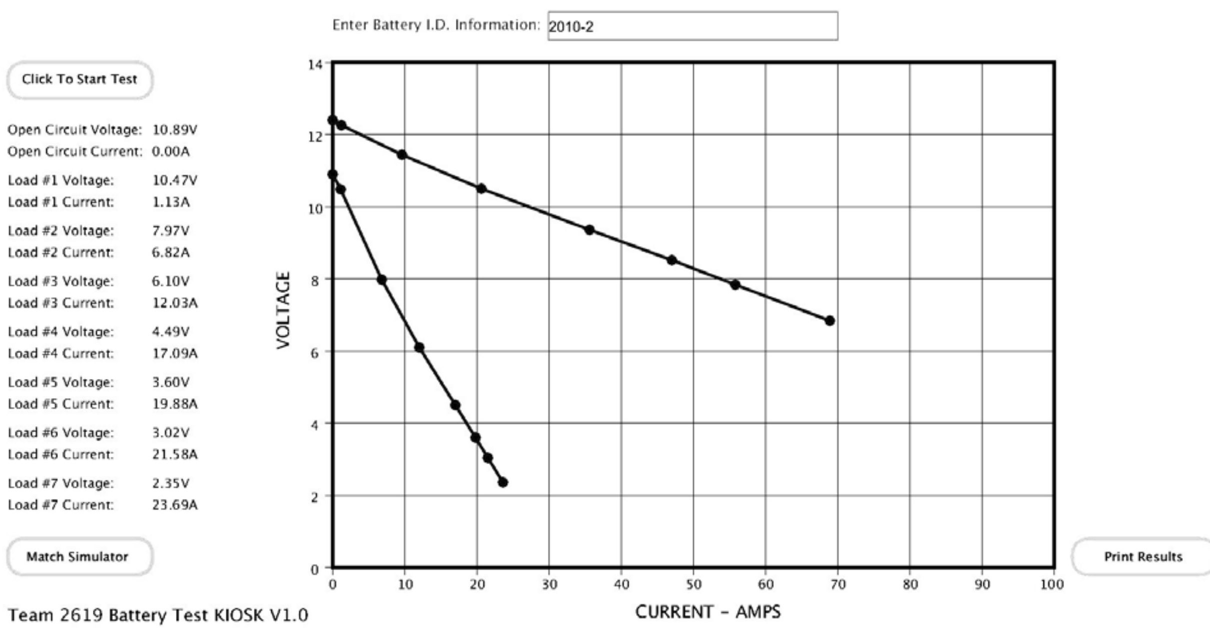
[14] Omar, Van den Bossche, Coosemans, Van Mierlo, "***Peukert Revisited—Critical Appraisal and Need for Modification for Lithium-Ion Batteries,"*** Brussels, Belgium: *Energies 2013*, *6*, pp. 5627.

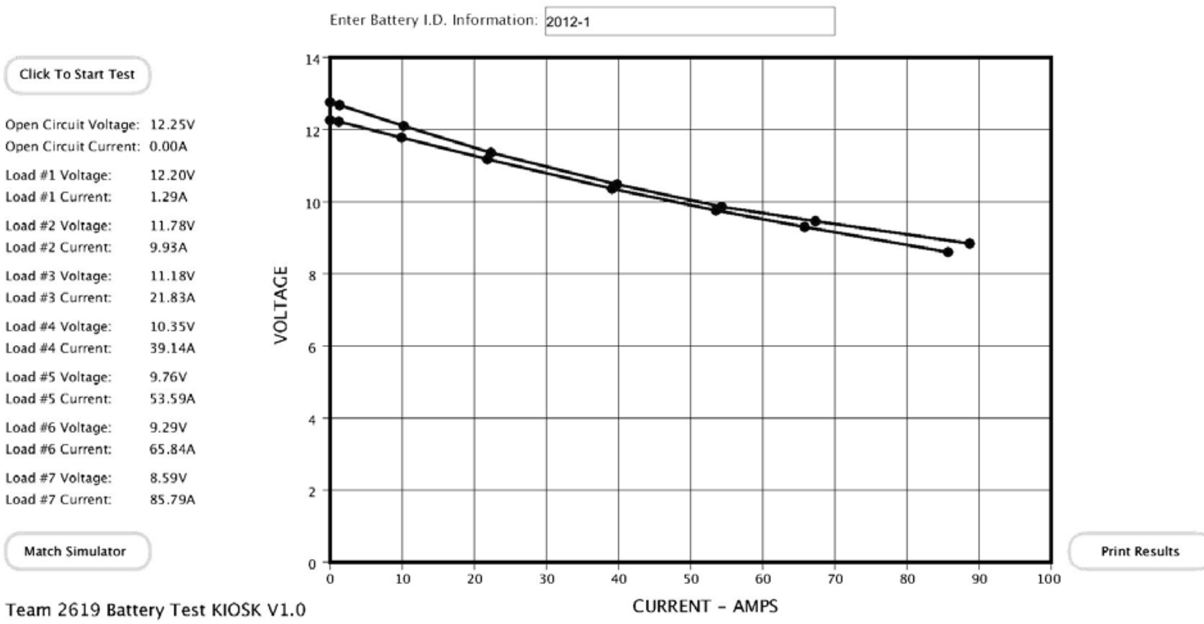
[15] Concorde Battery Corporation, "***Battery Technical Manual,***" Document 6-0101 Rev. D, West Covina, California, April 2014, pp. 27.

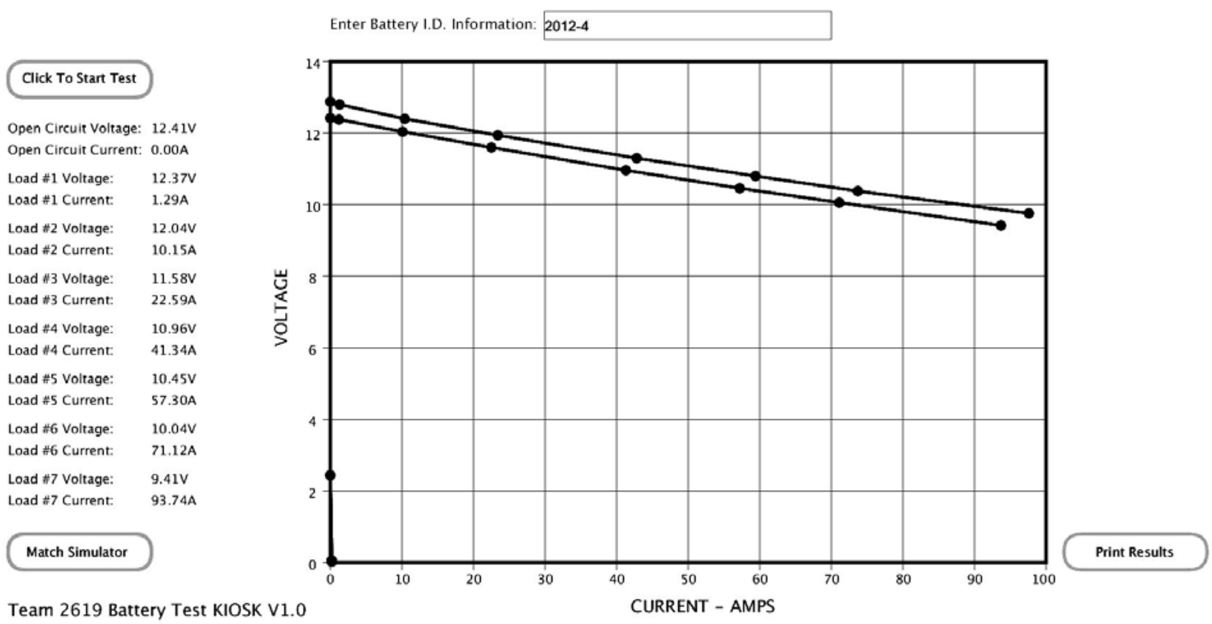
[16] Ericson Electric "***Glossary of Terms,***" www.ericson.com/downloads/**Glossary**-of-**terms.pdf**

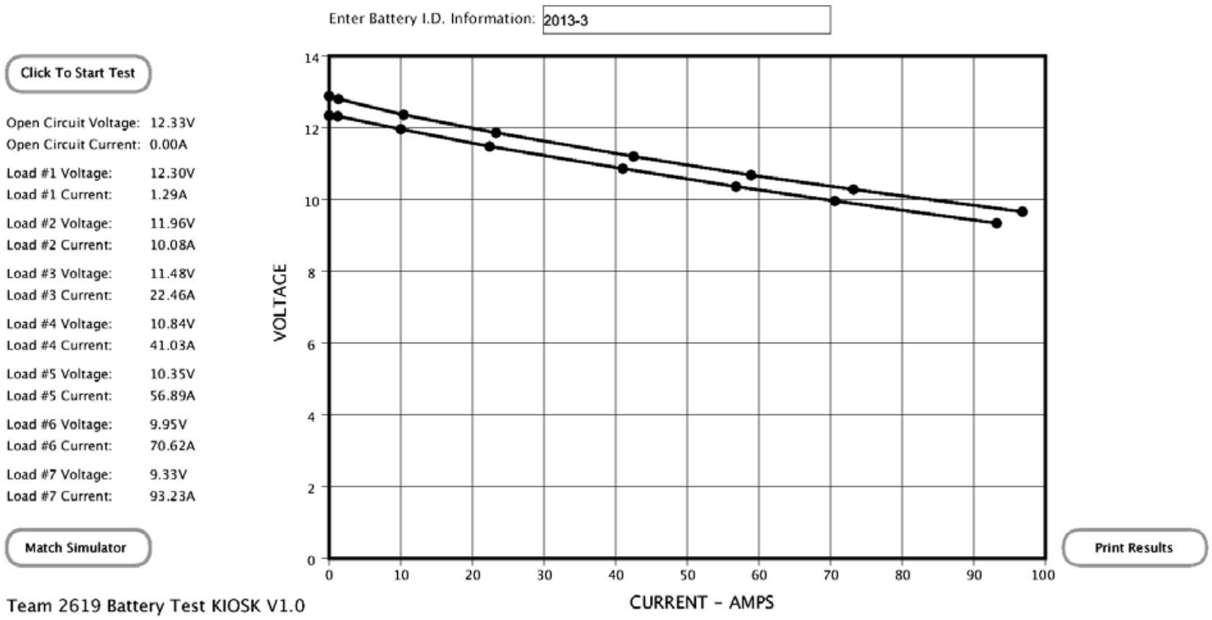
Appendix I – Result Data

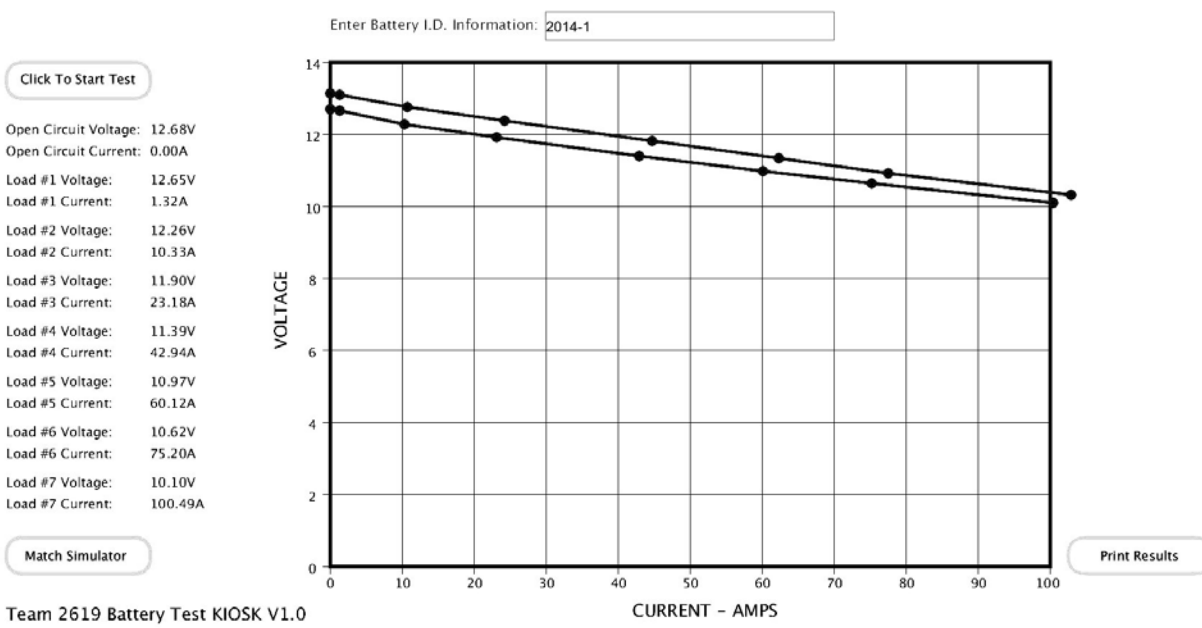


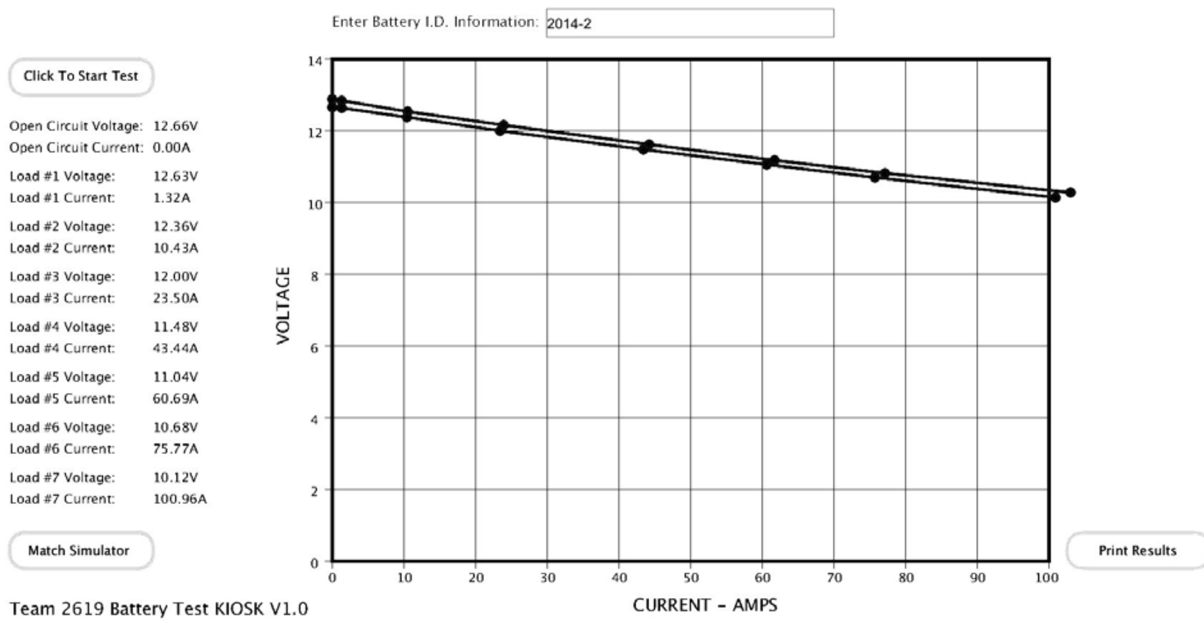


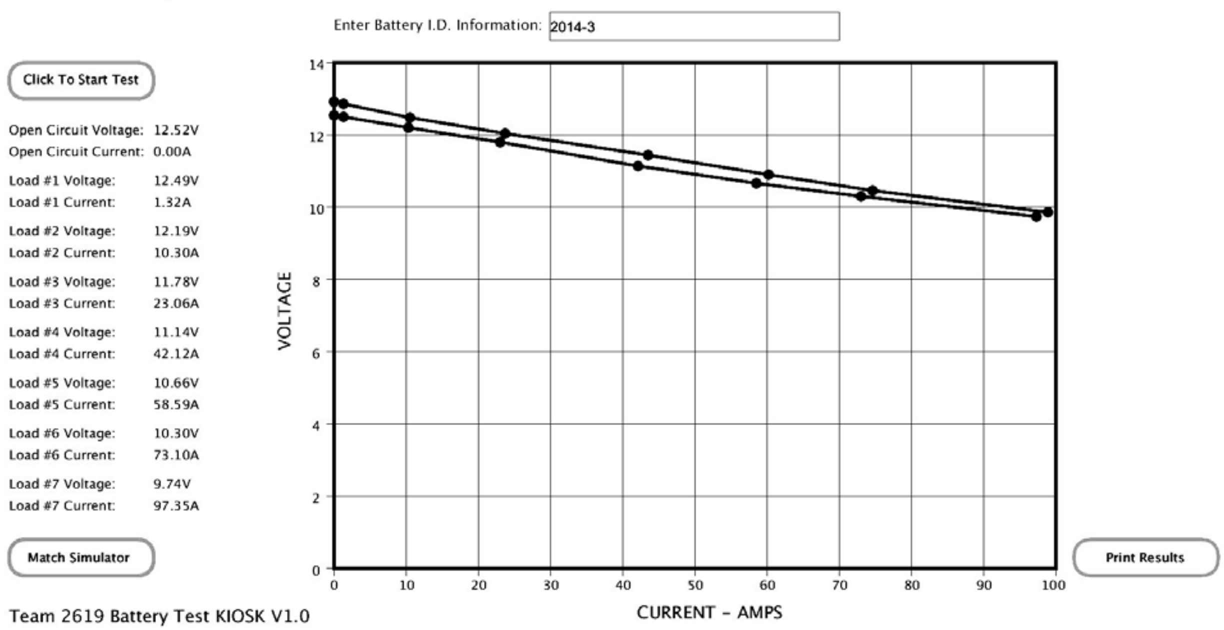

Enter Battery I.D. Information: 2012-1
Click To Start Test
Open Circuit Voltage: 12.25V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.20V
Load #1 Current: 1.29A
Load #2 Voltage: 11.78V
Load #2 Current: 9.93A
Load #3 Voltage: 11.18V
Load #3 Current: 21.83A
Load #4 Voltage: 10.35V
Load #4 Current: 39.14A
Load #5 Voltage: 9.76V
Load #5 Current: 53.59A
Load #6 Voltage: 9.29V
Load #6 Current: 65.84A
Load #7 Voltage: 8.59V
Load #7 Current: 85.79A
Match Simulator
Team 2619 Battery Test KIOSK V1.0
VOLTAGE
CURRENT - AMPS
Print Results

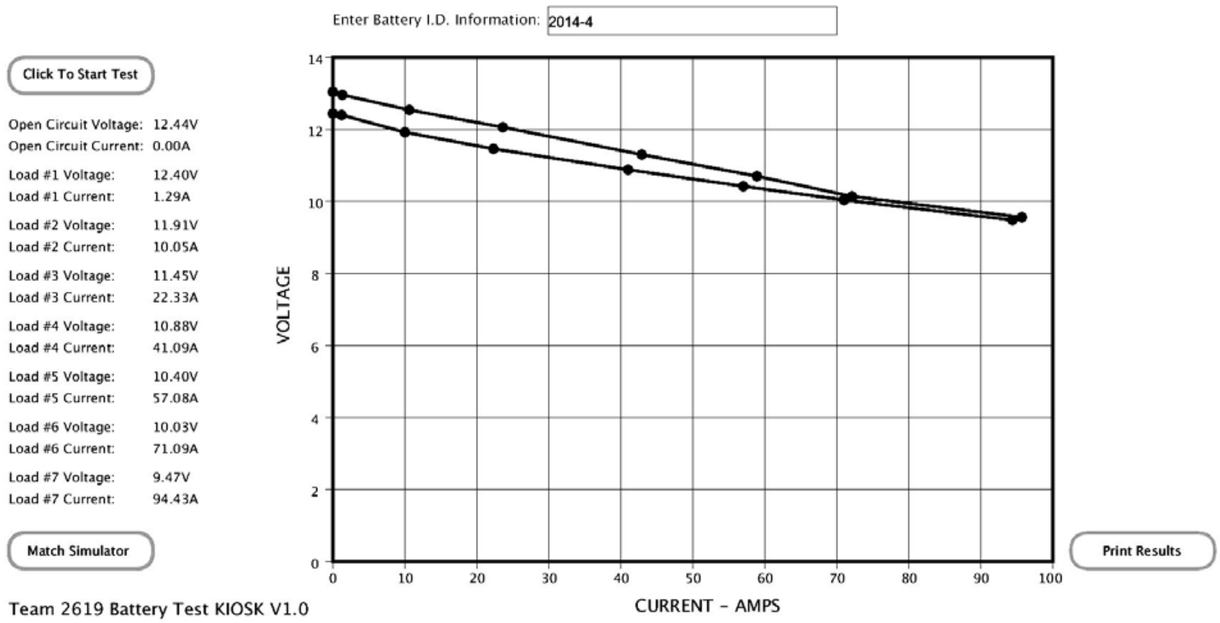

Enter Battery I.D. Information: 2012-4
Click To Start Test
Open Circuit Voltage: 12.41V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.37V
Load #1 Current: 1.29A
Load #2 Voltage: 12.04V
Load #2 Current: 10.15A
Load #3 Voltage: 11.58V
Load #3 Current: 22.59A
Load #4 Voltage: 10.96V
Load #4 Current: 41.34A
Load #5 Voltage: 10.45V
Load #5 Current: 57.30A
Load #6 Voltage: 10.04V
Load #6 Current: 71.12A
Load #7 Voltage: 9.41V
Load #7 Current: 93.74A
Match Simulator
Team 2619 Battery Test KIOSK V1.0
VOLTAGE
CURRENT - AMPS
Print Results

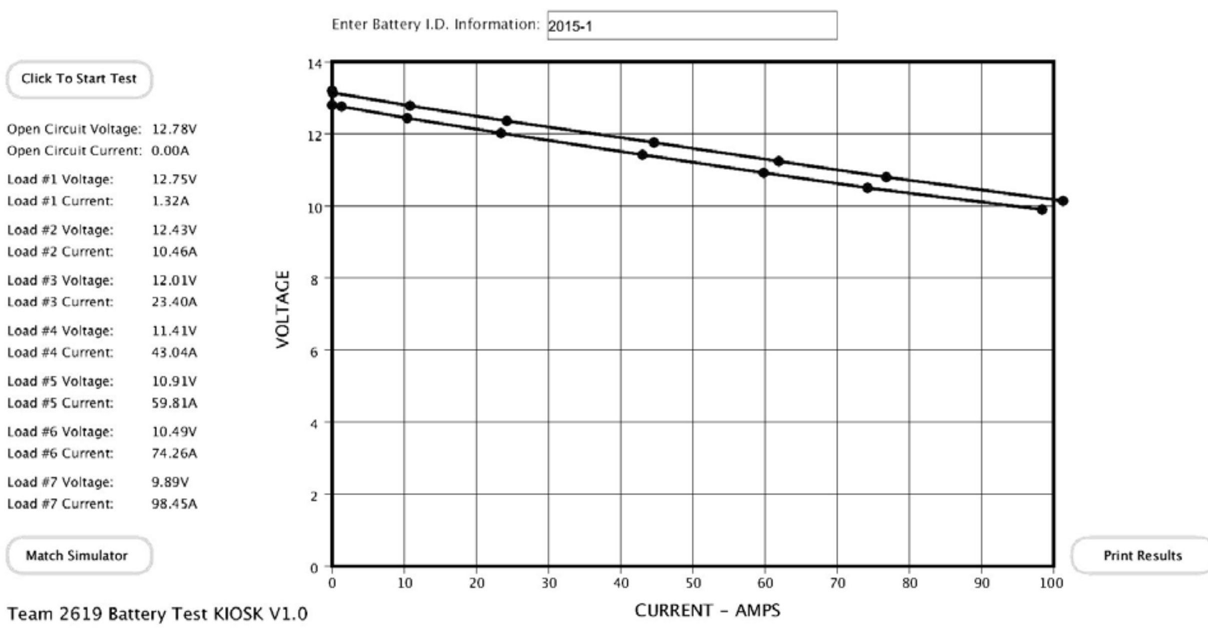

Enter Battery I.D. Information: 2013-3
Click To Start Test
Open Circuit Voltage: 12.33V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.30V
Load #1 Current: 1.29A
Load #2 Voltage: 11.96V
Load #2 Current: 10.08A
Load #3 Voltage: 11.48V
Load #3 Current: 22.46A
Load #4 Voltage: 10.84V
Load #4 Current: 41.03A
Load #5 Voltage: 10.35V
Load #5 Current: 56.89A
Load #6 Voltage: 9.95V
Load #6 Current: 70.62A
Load #7 Voltage: 9.33V
Load #7 Current: 93.23A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0

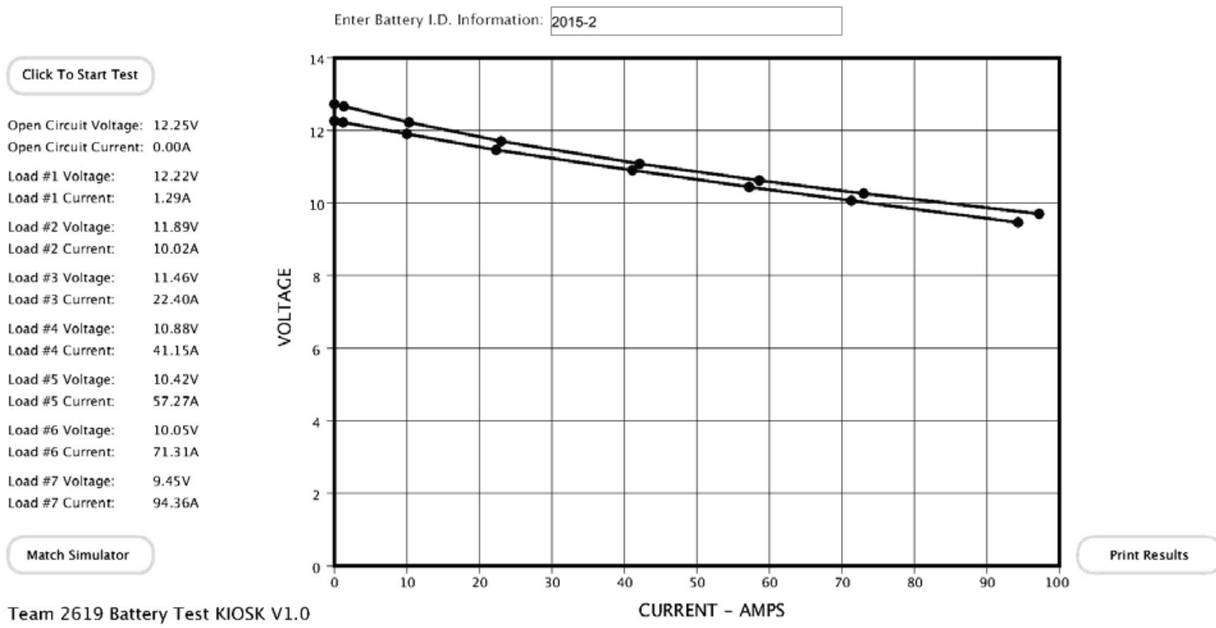

Enter Battery I.D. Information: 2014-1
Click To Start Test
Open Circuit Voltage: 12.68V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.65V
Load #1 Current: 1.32A
Load #2 Voltage: 12.26V
Load #2 Current: 10.33A
Load #3 Voltage: 11.90V
Load #3 Current: 23.18A
Load #4 Voltage: 11.39V
Load #4 Current: 42.94A
Load #5 Voltage: 10.97V
Load #5 Current: 60.12A
Load #6 Voltage: 10.62V
Load #6 Current: 75.20A
Load #7 Voltage: 10.10V
Load #7 Current: 100.49A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0

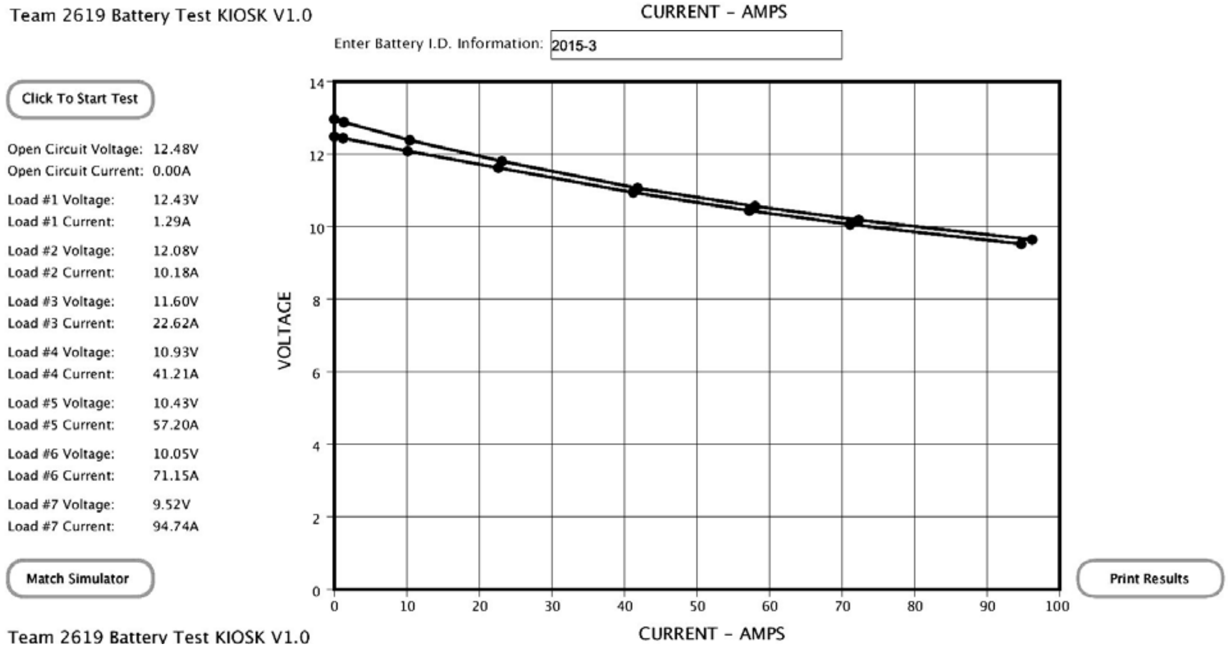

Enter Battery I.D. Information: 2014-2
Click To Start Test
Open Circuit Voltage: 12.66V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.63V
Load #1 Current: 1.32A
Load #2 Voltage: 12.36V
Load #2 Current: 10.43A
Load #3 Voltage: 12.00V
Load #3 Current: 23.50A
Load #4 Voltage: 11.48V
Load #4 Current: 43.44A
Load #5 Voltage: 11.04V
Load #5 Current: 60.69A
Load #6 Voltage: 10.68V
Load #6 Current: 75.77A
Load #7 Voltage: 10.12V
Load #7 Current: 100.96A
Match Simulator
VOLTAGE
CURRENT - AMPS
Print Results
Team 2619 Battery Test KIOSK V1.0

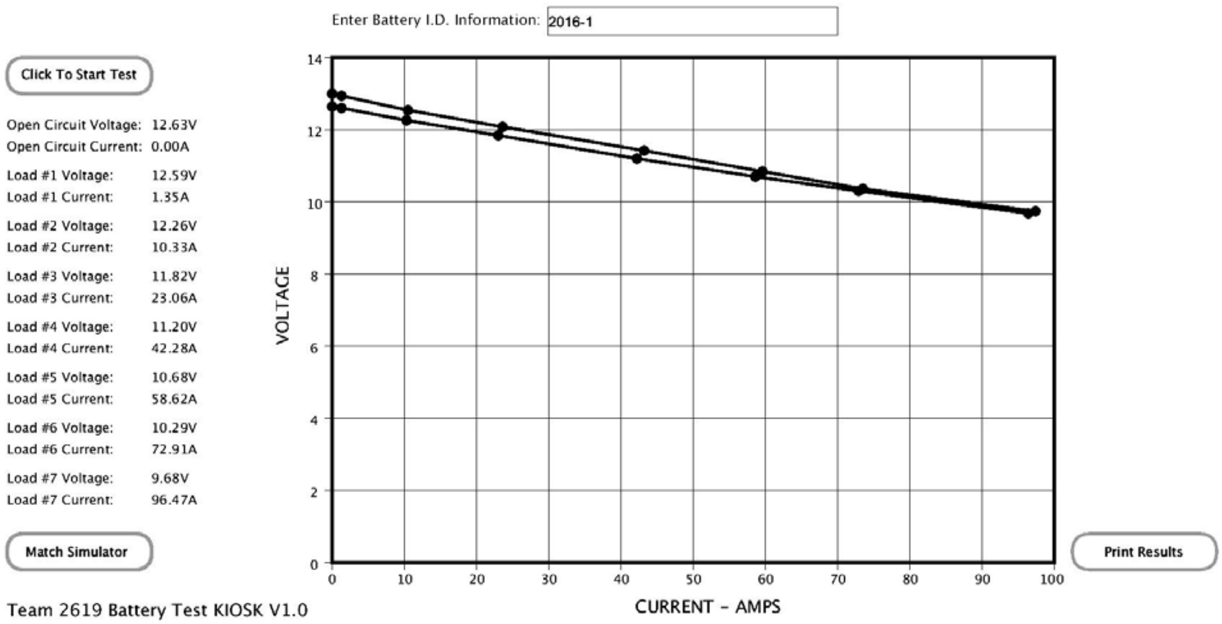

Enter Battery I.D. Information: 2014-3
Click To Start Test
Open Circuit Voltage: 12.52V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.49V
Load #1 Current: 1.32A
Load #2 Voltage: 12.19V
Load #2 Current: 10.30A
Load #3 Voltage: 11.78V
Load #3 Current: 23.06A
Load #4 Voltage: 11.14V
Load #4 Current: 42.12A
Load #5 Voltage: 10.66V
Load #5 Current: 58.59A
Load #6 Voltage: 10.30V
Load #6 Current: 73.10A
Load #7 Voltage: 9.74V
Load #7 Current: 97.35A
Match Simulator
VOLTAGE
CURRENT - AMPS
Print Results
Team 2619 Battery Test KIOSK V1.0

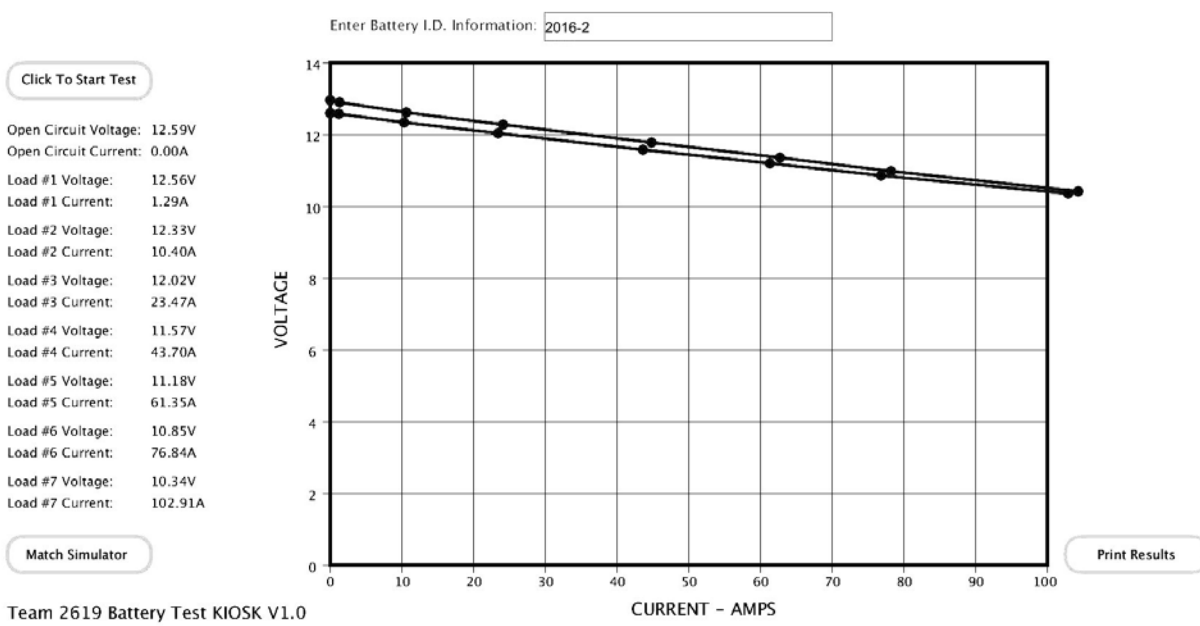

Enter Battery I.D. Information: 2014-4
Click To Start Test
Open Circuit Voltage: 12.44V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.40V
Load #1 Current: 1.29A
Load #2 Voltage: 11.91V
Load #2 Current: 10.05A
Load #3 Voltage: 11.45V
Load #3 Current: 22.33A
Load #4 Voltage: 10.88V
Load #4 Current: 41.09A
Load #5 Voltage: 10.40V
Load #5 Current: 57.08A
Load #6 Voltage: 10.03V
Load #6 Current: 71.09A
Load #7 Voltage: 9.47V
Load #7 Current: 94.43A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0

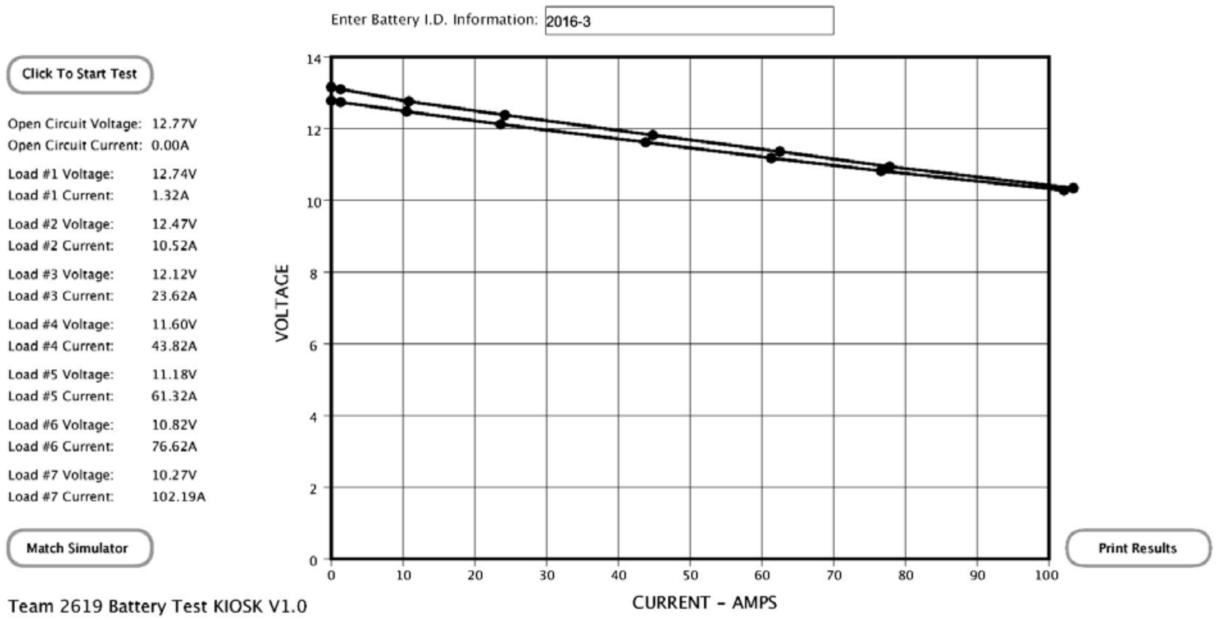

Enter Battery I.D. Information: 2015-1
Click To Start Test
Open Circuit Voltage: 12.78V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.75V
Load #1 Current: 1.32A
Load #2 Voltage: 12.43V
Load #2 Current: 10.46A
Load #3 Voltage: 12.01V
Load #3 Current: 23.40A
Load #4 Voltage: 11.41V
Load #4 Current: 43.04A
Load #5 Voltage: 10.91V
Load #5 Current: 59.81A
Load #6 Voltage: 10.49V
Load #6 Current: 74.26A
Load #7 Voltage: 9.89V
Load #7 Current: 98.45A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0

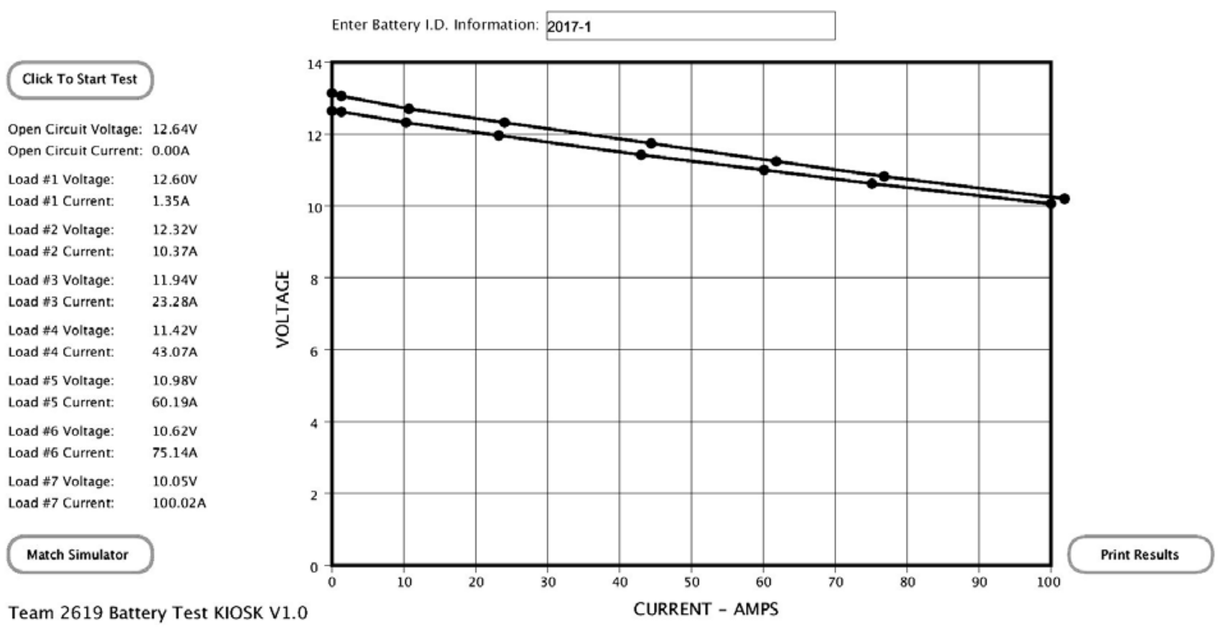

Enter Battery I.D. Information: 2015-2
Click To Start Test
Open Circuit Voltage: 12.25V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.22V
Load #1 Current: 1.29A
Load #2 Voltage: 11.89V
Load #2 Current: 10.02A
Load #3 Voltage: 11.46V
Load #3 Current: 22.40A
Load #4 Voltage: 10.88V
Load #4 Current: 41.15A
Load #5 Voltage: 10.42V
Load #5 Current: 57.27A
Load #6 Voltage: 10.05V
Load #6 Current: 71.31A
Load #7 Voltage: 9.45V
Load #7 Current: 94.36A
Match Simulator
VOLTAGE
CURRENT - AMPS
Print Results
Team 2619 Battery Test KIOSK V1.0

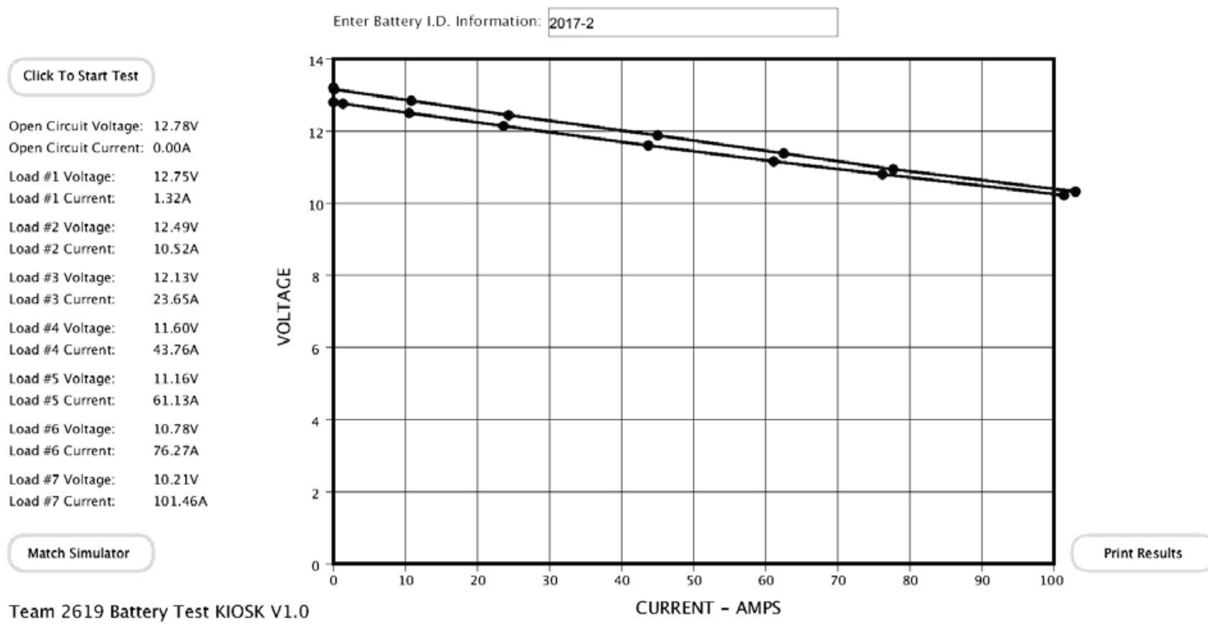

Enter Battery I.D. Information: 2015-3
Click To Start Test
Open Circuit Voltage: 12.48V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.43V
Load #1 Current: 1.29A
Load #2 Voltage: 12.08V
Load #2 Current: 10.18A
Load #3 Voltage: 11.60V
Load #3 Current: 22.62A
Load #4 Voltage: 10.93V
Load #4 Current: 41.21A
Load #5 Voltage: 10.43V
Load #5 Current: 57.20A
Load #6 Voltage: 10.05V
Load #6 Current: 71.15A
Load #7 Voltage: 9.52V
Load #7 Current: 94.74A
Match Simulator
VOLTAGE
CURRENT - AMPS
Print Results
Team 2619 Battery Test KIOSK V1.0

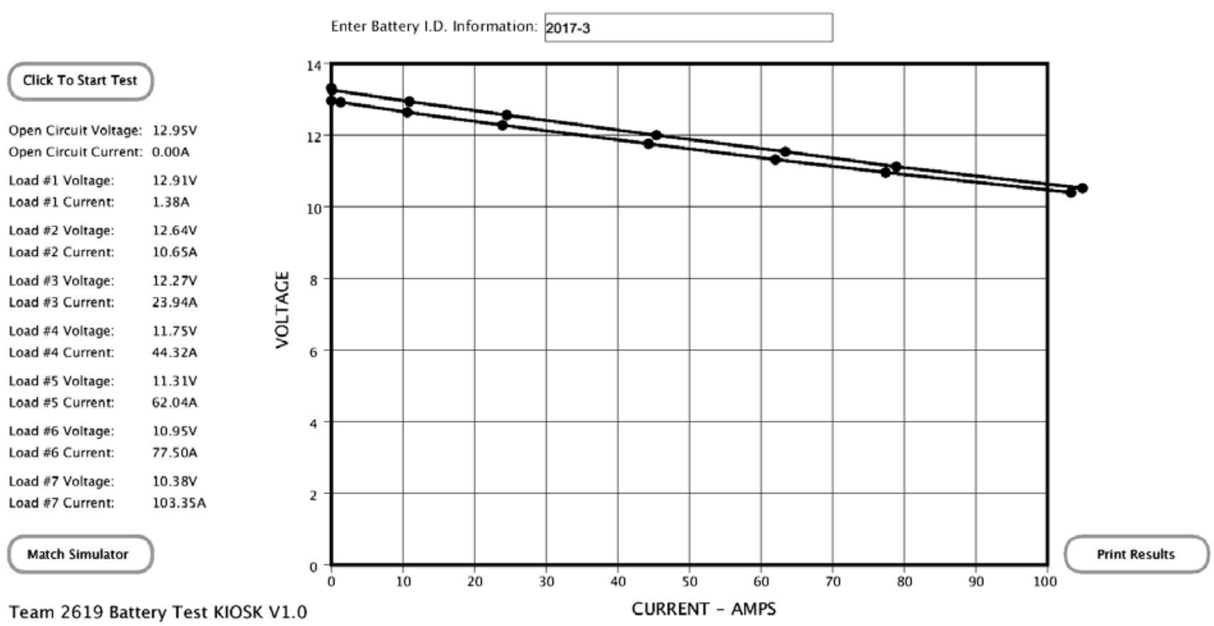

Enter Battery I.D. Information: 2016-1
Click To Start Test
Open Circuit Voltage: 12.63V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.59V
Load #1 Current: 1.35A
Load #2 Voltage: 12.26V
Load #2 Current: 10.33A
Load #3 Voltage: 11.82V
Load #3 Current: 23.06A
Load #4 Voltage: 11.20V
Load #4 Current: 42.28A
Load #5 Voltage: 10.68V
Load #5 Current: 58.62A
Load #6 Voltage: 10.29V
Load #6 Current: 72.91A
Load #7 Voltage: 9.68V
Load #7 Current: 96.47A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0


Enter Battery I.D. Information: 2016-2
Click To Start Test
Open Circuit Voltage: 12.59V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.56V
Load #1 Current: 1.29A
Load #2 Voltage: 12.33V
Load #2 Current: 10.40A
Load #3 Voltage: 12.02V
Load #3 Current: 23.47A
Load #4 Voltage: 11.57V
Load #4 Current: 43.70A
Load #5 Voltage: 11.18V
Load #5 Current: 61.35A
Load #6 Voltage: 10.85V
Load #6 Current: 76.84A
Load #7 Voltage: 10.34V
Load #7 Current: 102.91A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0


Enter Battery I.D. Information: 2016-3
Click To Start Test
Open Circuit Voltage: 12.77V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.74V
Load #1 Current: 1.32A
Load #2 Voltage: 12.47V
Load #2 Current: 10.52A
Load #3 Voltage: 12.12V
Load #3 Current: 23.62A
Load #4 Voltage: 11.60V
Load #4 Current: 43.82A
Load #5 Voltage: 11.18V
Load #5 Current: 61.32A
Load #6 Voltage: 10.82V
Load #6 Current: 76.62A
Load #7 Voltage: 10.27V
Load #7 Current: 102.19A
Match Simulator
VOLTAGE
CURRENT - AMPS
Print Results
Team 2619 Battery Test KIOSK V1.0


Enter Battery I.D. Information: 2017-1
Click To Start Test
Open Circuit Voltage: 12.64V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.60V
Load #1 Current: 1.35A
Load #2 Voltage: 12.32V
Load #2 Current: 10.37A
Load #3 Voltage: 11.94V
Load #3 Current: 23.28A
Load #4 Voltage: 11.42V
Load #4 Current: 43.07A
Load #5 Voltage: 10.98V
Load #5 Current: 60.19A
Load #6 Voltage: 10.62V
Load #6 Current: 75.14A
Load #7 Voltage: 10.05V
Load #7 Current: 100.02A
Match Simulator
VOLTAGE
CURRENT - AMPS
Print Results
Team 2619 Battery Test KIOSK V1.0


Enter Battery I.D. Information: 2017-2
Click To Start Test
Open Circuit Voltage: 12.78V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.75V
Load #1 Current: 1.32A
Load #2 Voltage: 12.49V
Load #2 Current: 10.52A
Load #3 Voltage: 12.13V
Load #3 Current: 23.65A
Load #4 Voltage: 11.60V
Load #4 Current: 43.76A
Load #5 Voltage: 11.16V
Load #5 Current: 61.13A
Load #6 Voltage: 10.78V
Load #6 Current: 76.27A
Load #7 Voltage: 10.21V
Load #7 Current: 101.46A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0


Enter Battery I.D. Information: 2017-3
Click To Start Test
Open Circuit Voltage: 12.95V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.91V
Load #1 Current: 1.38A
Load #2 Voltage: 12.64V
Load #2 Current: 10.65A
Load #3 Voltage: 12.27V
Load #3 Current: 23.94A
Load #4 Voltage: 11.75V
Load #4 Current: 44.32A
Load #5 Voltage: 11.31V
Load #5 Current: 62.04A
Load #6 Voltage: 10.95V
Load #6 Current: 77.50A
Load #7 Voltage: 10.38V
Load #7 Current: 103.35A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0

Enter Battery I.D. Information: 2017-4

Click To Start Test

Open Circuit Voltage: 12.79V
Open Circuit Current: 0.00A

Load #1 Voltage: 12.75V
Load #1 Current: 1.35A

Load #2 Voltage: 12.45V
Load #2 Current: 10.52A

Load #3 Voltage: 12.06V
Load #3 Current: 23.59A

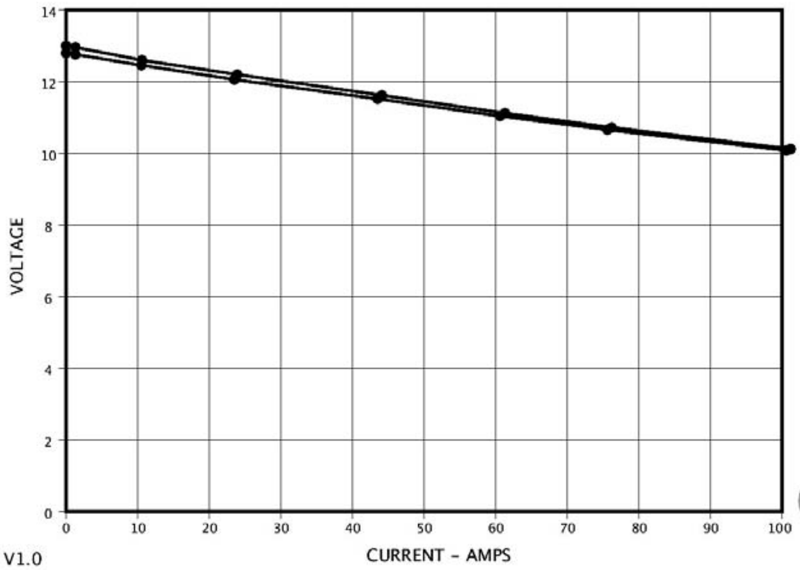
Load #4 Voltage: 11.50V
Load #4 Current: 43.57A

Load #5 Voltage: 11.04V
Load #5 Current: 60.69A

Load #6 Voltage: 10.65V
Load #6 Current: 75.67A

Load #7 Voltage: 10.07V
Load #7 Current: 100.62A

Match Simulator



Print Results

Team 2619 Battery Test KIOSK V1.0

Enter Battery I.D. Information: 2017-5

Click To Start Test

Open Circuit Voltage: 12.84V
Open Circuit Current: 0.00A

Load #1 Voltage: 12.81V
Load #1 Current: 1.35A

Load #2 Voltage: 12.53V
Load #2 Current: 10.55A

Load #3 Voltage: 12.16V
Load #3 Current: 23.72A

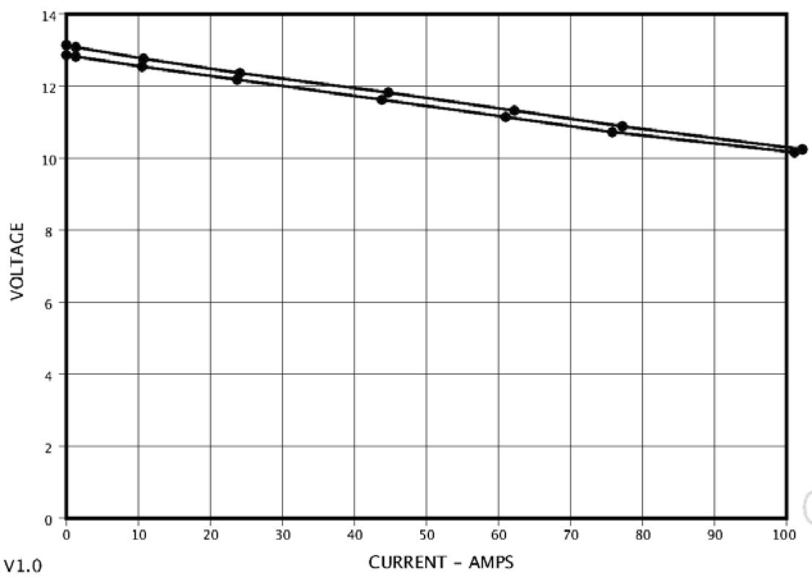
Load #4 Voltage: 11.61V
Load #4 Current: 43.82A

Load #5 Voltage: 11.13V
Load #5 Current: 61.07A

Load #6 Voltage: 10.72V
Load #6 Current: 75.89A

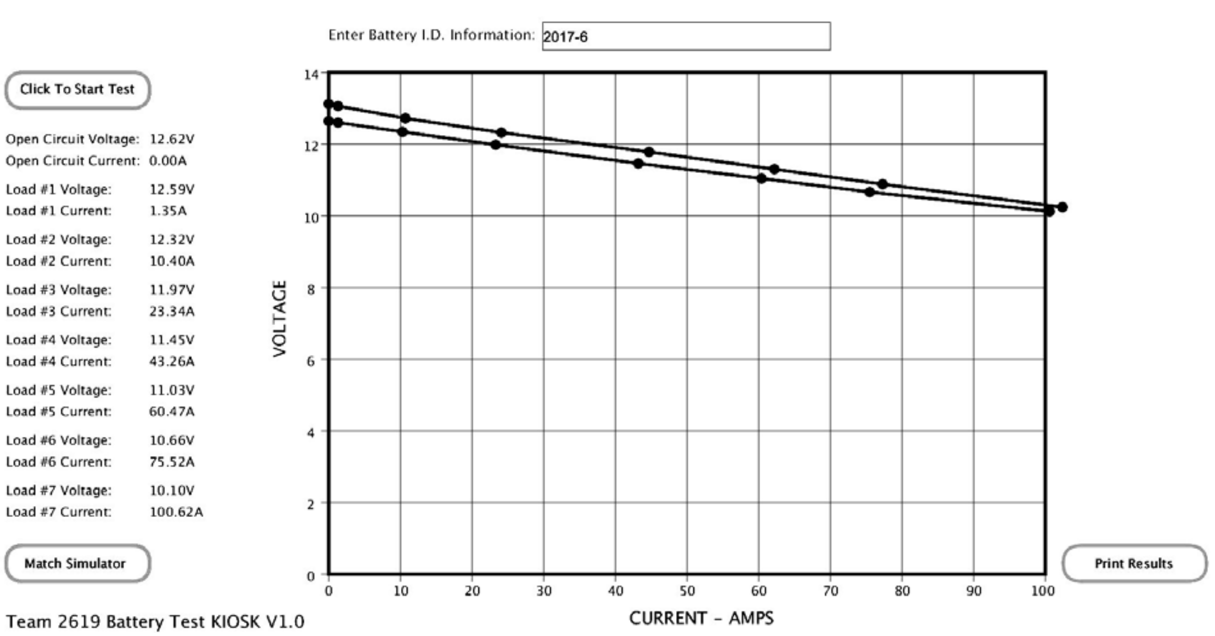
Load #7 Voltage: 10.16V
Load #7 Current: 101.12A

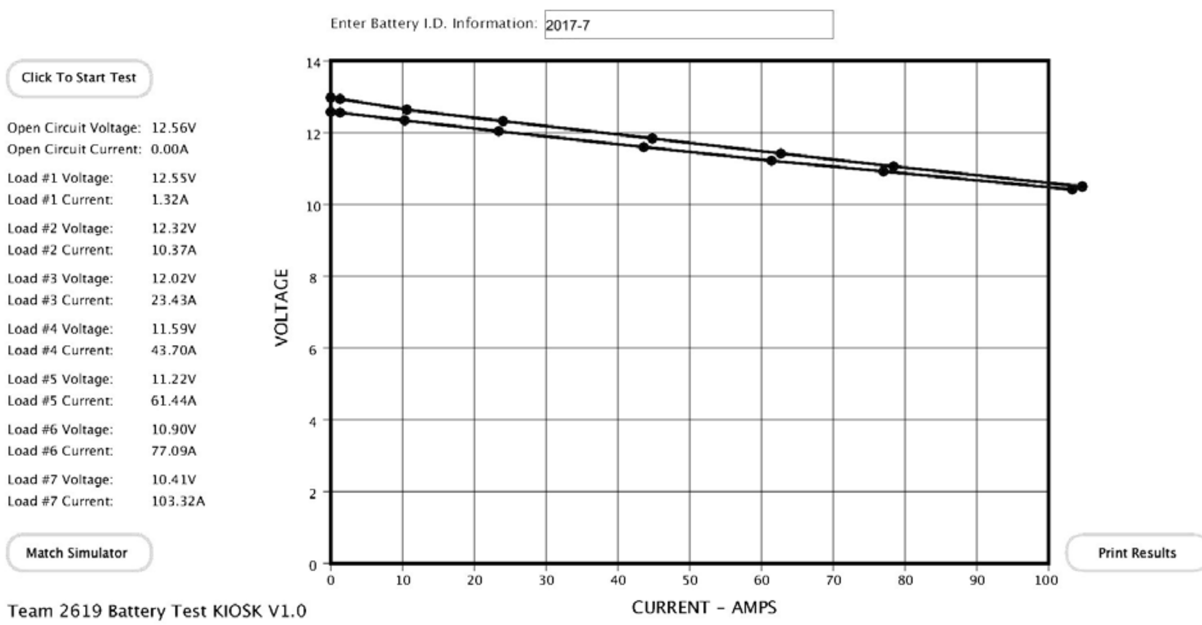
Match Simulator

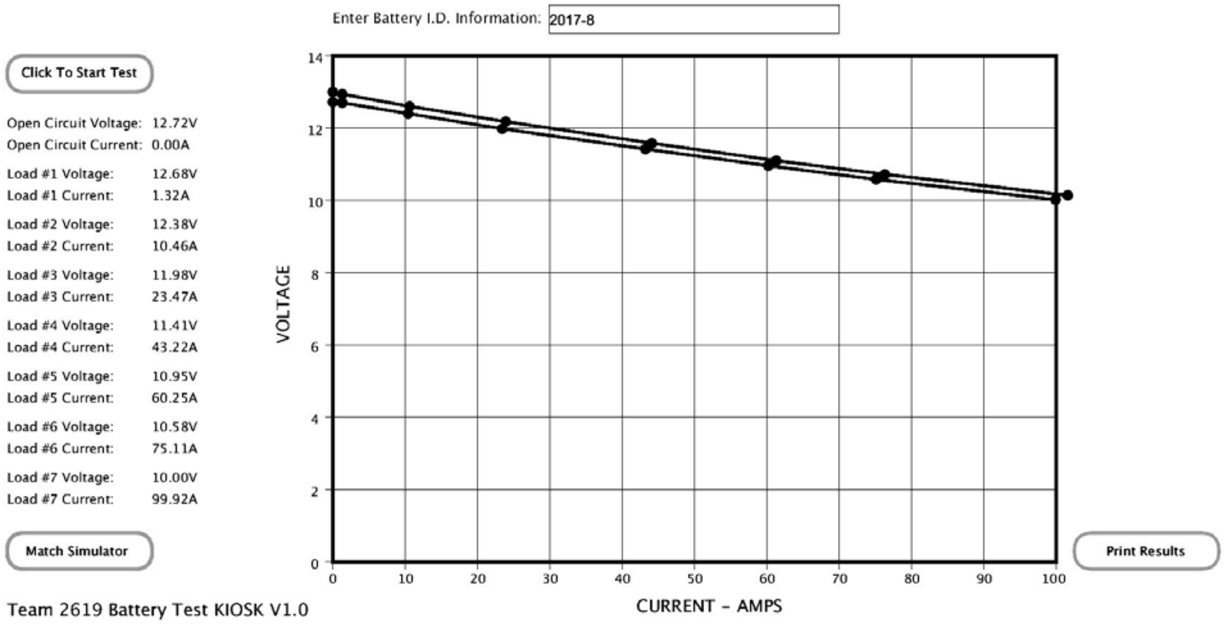


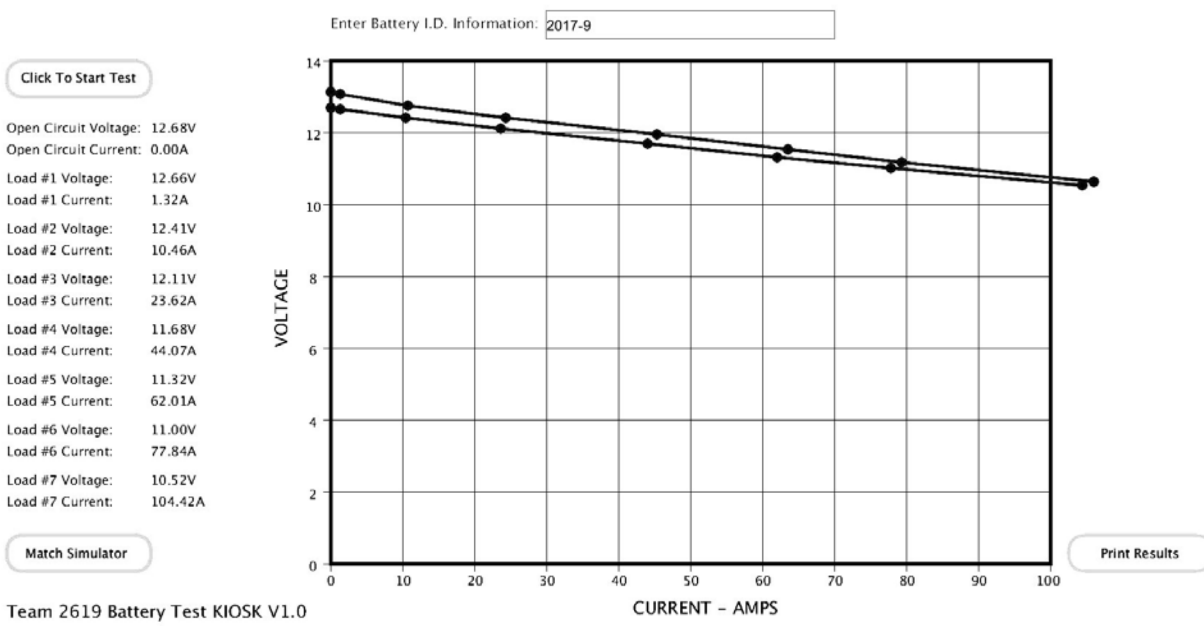
Print Results

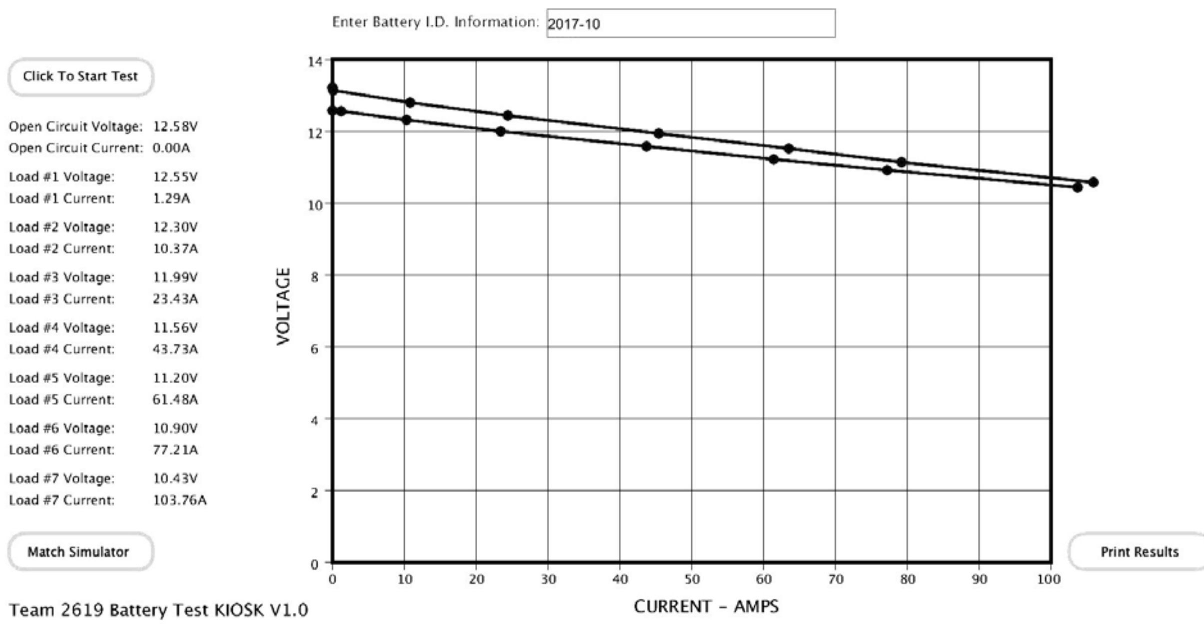
Team 2619 Battery Test KIOSK V1.0

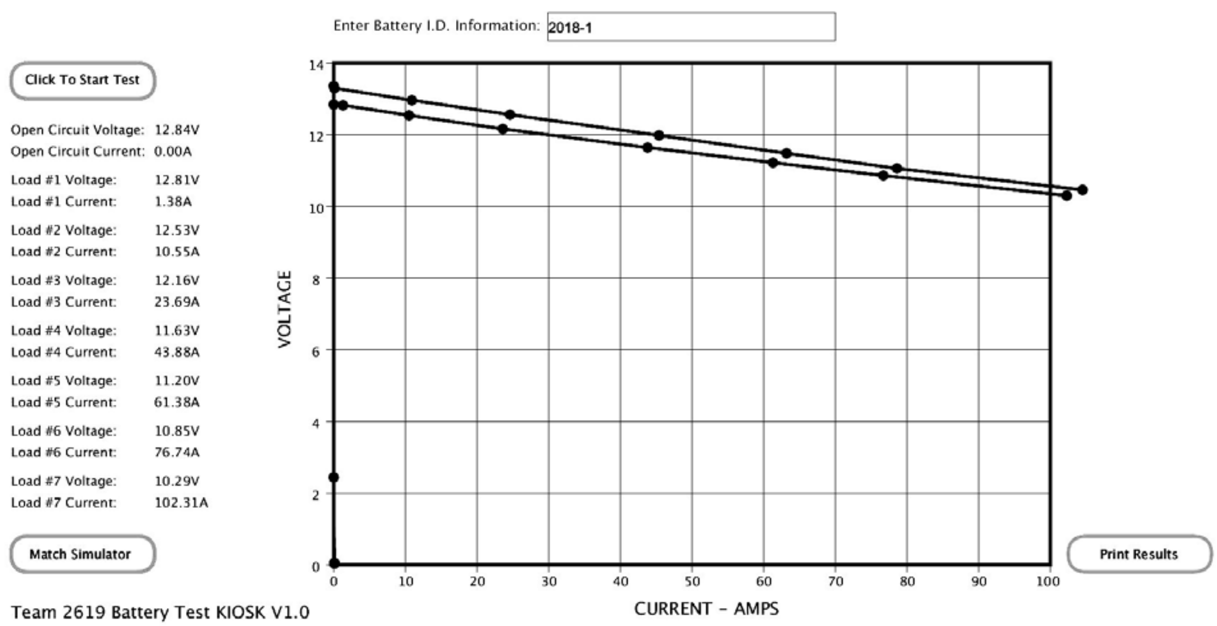

Enter Battery I.D. Information: 2017-6
Click To Start Test
Open Circuit Voltage: 12.62V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.59V
Load #1 Current: 1.35A
Load #2 Voltage: 12.32V
Load #2 Current: 10.40A
Load #3 Voltage: 11.97V
Load #3 Current: 23.34A
Load #4 Voltage: 11.45V
Load #4 Current: 43.26A
Load #5 Voltage: 11.03V
Load #5 Current: 60.47A
Load #6 Voltage: 10.66V
Load #6 Current: 75.52A
Load #7 Voltage: 10.10V
Load #7 Current: 100.62A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0

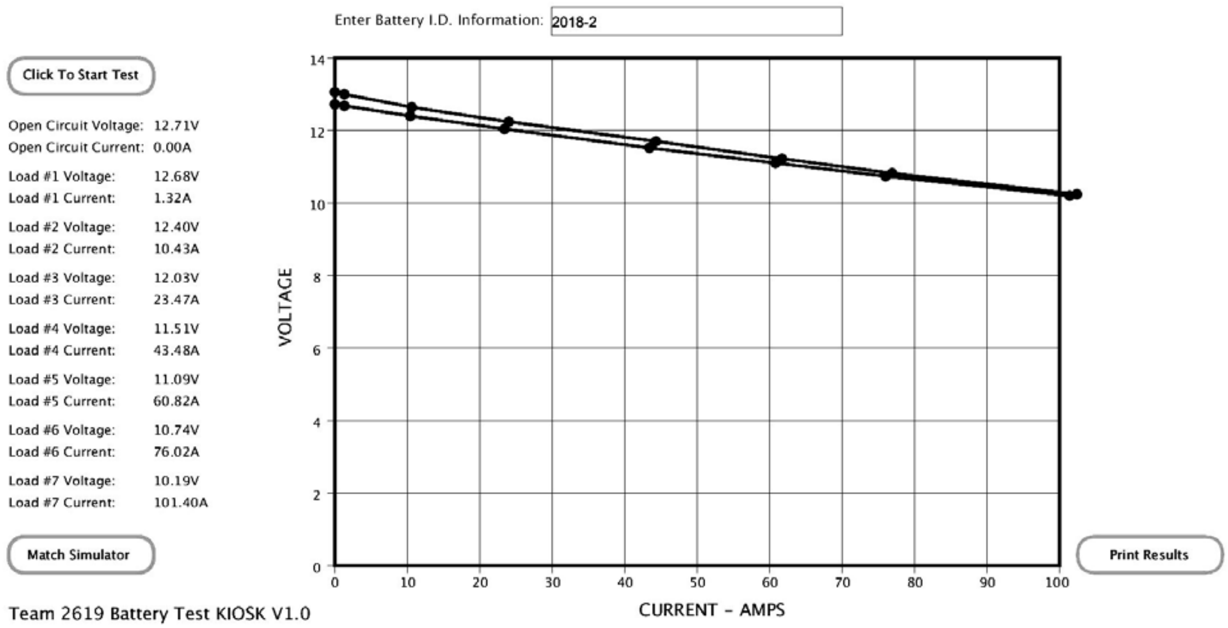

Enter Battery I.D. Information: 2017-7
Click To Start Test
Open Circuit Voltage: 12.56V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.55V
Load #1 Current: 1.32A
Load #2 Voltage: 12.32V
Load #2 Current: 10.37A
Load #3 Voltage: 12.02V
Load #3 Current: 23.43A
Load #4 Voltage: 11.59V
Load #4 Current: 43.70A
Load #5 Voltage: 11.22V
Load #5 Current: 61.44A
Load #6 Voltage: 10.90V
Load #6 Current: 77.09A
Load #7 Voltage: 10.41V
Load #7 Current: 103.32A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0

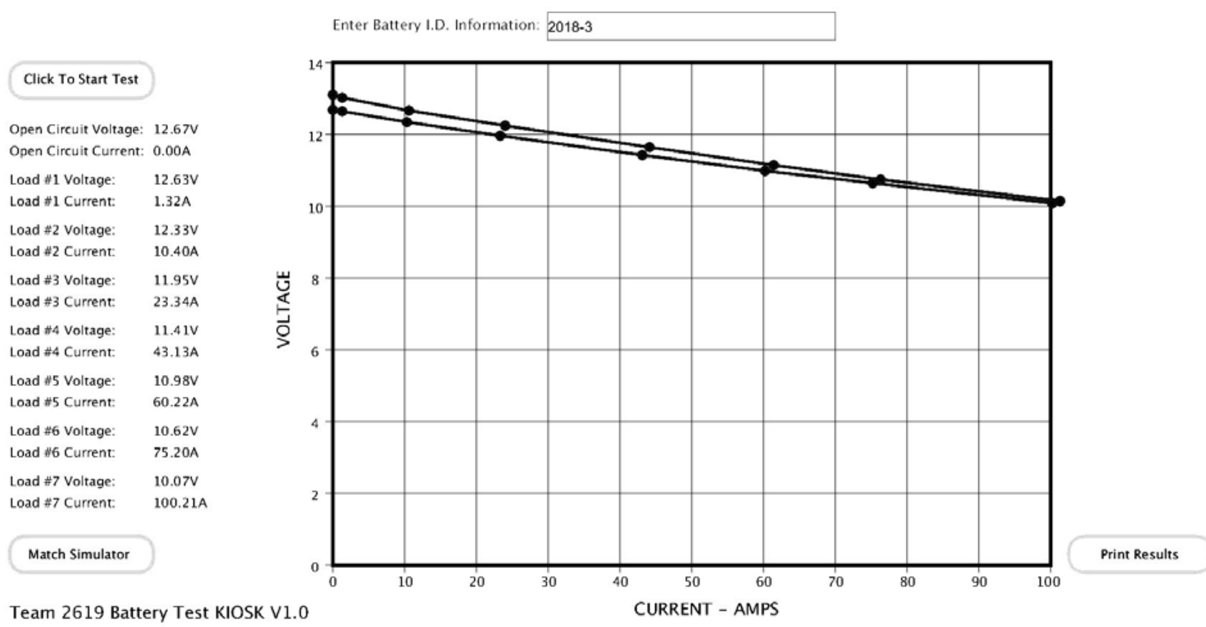

Enter Battery I.D. Information: 2017-8
Click To Start Test
Open Circuit Voltage: 12.72V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.68V
Load #1 Current: 1.32A
Load #2 Voltage: 12.38V
Load #2 Current: 10.46A
Load #3 Voltage: 11.98V
Load #3 Current: 23.47A
Load #4 Voltage: 11.41V
Load #4 Current: 43.22A
Load #5 Voltage: 10.95V
Load #5 Current: 60.25A
Load #6 Voltage: 10.58V
Load #6 Current: 75.11A
Load #7 Voltage: 10.00V
Load #7 Current: 99.92A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0


Enter Battery I.D. Information: 2017-9
Click To Start Test
Open Circuit Voltage: 12.68V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.66V
Load #1 Current: 1.32A
Load #2 Voltage: 12.41V
Load #2 Current: 10.46A
Load #3 Voltage: 12.11V
Load #3 Current: 23.62A
Load #4 Voltage: 11.68V
Load #4 Current: 44.07A
Load #5 Voltage: 11.32V
Load #5 Current: 62.01A
Load #6 Voltage: 11.00V
Load #6 Current: 77.84A
Load #7 Voltage: 10.52V
Load #7 Current: 104.42A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0


Enter Battery I.D. Information: 2017-10
Click To Start Test
Open Circuit Voltage: 12.58V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.55V
Load #1 Current: 1.29A
Load #2 Voltage: 12.30V
Load #2 Current: 10.37A
Load #3 Voltage: 11.99V
Load #3 Current: 23.43A
Load #4 Voltage: 11.56V
Load #4 Current: 43.73A
Load #5 Voltage: 11.20V
Load #5 Current: 61.48A
Load #6 Voltage: 10.90V
Load #6 Current: 77.21A
Load #7 Voltage: 10.43V
Load #7 Current: 103.76A
Match Simulator
Print Results
VOLTAGE
0 2 4 6 8 10 12 14
0 10 20 30 40 50 60 70 80 90 100
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0


Enter Battery I.D. Information: 2018-1
Click To Start Test
Open Circuit Voltage: 12.84V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.81V
Load #1 Current: 1.38A
Load #2 Voltage: 12.53V
Load #2 Current: 10.55A
Load #3 Voltage: 12.16V
Load #3 Current: 23.69A
Load #4 Voltage: 11.63V
Load #4 Current: 43.88A
Load #5 Voltage: 11.20V
Load #5 Current: 61.38A
Load #6 Voltage: 10.85V
Load #6 Current: 76.74A
Load #7 Voltage: 10.29V
Load #7 Current: 102.31A
Match Simulator
Print Results
VOLTAGE
0 2 4 6 8 10 12 14
0 10 20 30 40 50 60 70 80 90 100
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0


Enter Battery I.D. Information: 2018-2
Click To Start Test
Open Circuit Voltage: 12.71V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.68V
Load #1 Current: 1.32A
Load #2 Voltage: 12.40V
Load #2 Current: 10.43A
Load #3 Voltage: 12.03V
Load #3 Current: 23.47A
Load #4 Voltage: 11.51V
Load #4 Current: 43.48A
Load #5 Voltage: 11.09V
Load #5 Current: 60.82A
Load #6 Voltage: 10.74V
Load #6 Current: 76.02A
Load #7 Voltage: 10.19V
Load #7 Current: 101.40A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0


Enter Battery I.D. Information: 2018-3
Click To Start Test
Open Circuit Voltage: 12.67V
Open Circuit Current: 0.00A
Load #1 Voltage: 12.63V
Load #1 Current: 1.32A
Load #2 Voltage: 12.33V
Load #2 Current: 10.40A
Load #3 Voltage: 11.95V
Load #3 Current: 23.34A
Load #4 Voltage: 11.41V
Load #4 Current: 43.13A
Load #5 Voltage: 10.98V
Load #5 Current: 60.22A
Load #6 Voltage: 10.62V
Load #6 Current: 75.20A
Load #7 Voltage: 10.07V
Load #7 Current: 100.21A
Match Simulator
Print Results
VOLTAGE
CURRENT - AMPS
Team 2619 Battery Test KIOSK V1.0

Appendix II – Standards Cover Pages

SAE International™ SURFACE VEHICLE STANDARD	SAE J240	REV. OCT2002
	Issued 1971-05 Revised 2002-10 Superseding J240 JUN1993	

Life Test for Automotive Storage Batteries

1. ***Scope***—This SAE Standard applies to 12 V, automotive storage batteries of 180 min or less reserve capacity. This life test simulates automotive service when the battery operates in a voltage regulated charging system. It subjects the battery to charge and discharge cycles comparable to those encountered in automotive service. Other performance and dimensional information is contained in the latest issue of SAE J537.

This document is intended as a guide toward standard practice, but may be subject to change to keep pace with experience and technical advances.

2. ***Reference***

2.1 **Applicable Publication**—The following publication forms a part of the specification to the extent specified herein. Unless otherwise indicated, the latest revision of SAE publications shall apply.

2.1.1 SAE Publication—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J537—Storage Batteries

3. ***Testing Procedure***

3.1 Cycle life testing shall begin within sixty days of the final nondestructive test as shown in 3.3 of SAE J537 (Table 1).

3.2 The battery is tested in a water bath maintained at 41 °C ± 3 °C (105 °F ± 5 °F).

3.3 Water level of the bath specified in 3.2 is to be maintained at a height equal to or greater than 75% of the overall height of the battery container or within 12 mm (1/2 in) of the metal bushing of side terminal batteries.

3.4 The test cycle is performed as follows:

Discharge 4 min ± 1 s at 25 A ± 0.1 A.

Charge:

a. Maximum voltage (at battery cable terminals): 14.8 V ± 0.03 V
b. Maximum rate: 25 A ± 0.1 A
c. Time: 10 min ± 3 s

SAE The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL
400 Commonwealth Drive, Warrendale, PA 15096-0001

SURFACE VEHICLE STANDARD

SAE J537

REV. SEP2000

Issued 1914-01
Revised 2000-09

Superseding J537 JUN94

Submitted for recognition as an American National Standard

(R) Storage Batteries

1. *Scope*—This SAE Standard serves as a guide for testing procedures of automotive 12 V storage batteries and as a publication providing information on container holddown configuration and terminal geometry.

1.1 The ratings submitted are to be based on procedures described in this document. The ratings submitted must be of a level that when any subsequent significant sample is tested in accordance with this document, that at least 90% of the batteries shall meet the ratings. The choice of 90% compliance recognizes that batteries consist of many plates and require chemical-electrical formation procedures and small variations in test conditions and procedures can affect the performance of individual batteries.

1.2 **Applications**—This document applies to lead-acid types of storage batteries used in motor vehicles, motorboats, tractors, and starting, lighting, and ignition (SLI) applications which use regulated charging systems.

2. *References*

2.1 **Applicable Publications**—The following publications form a part of this specification to the extent specified herein. The latest issue of SAE publications shall apply.

2.1.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J240—Life Test for Automotive Storage Batteries
SAE J1495—Test Procedure for Battery Flame Retardant Venting Systems
SAE J2185—Life Test for Heavy-Duty Storage Batteries

3. *Electrical Testing Procedure*—Individual battery performance values are to be determined by the procedures outlined under Sampling, Conditioning, and Sequence of Tests.

Danger of Exploding Batteries

Batteries contain sulfuric acid and they produce explosive mixtures of hydrogen and oxygen. Because self-discharge action generates hydrogen gas even when the battery is not in operation, make sure batteries are stored and worked on in a well-ventilated area. ALWAYS wear safety goggles and a face shield when working on or near batteries. When working with batteries:

UL 2054

Underwriters Laboratories Inc.
Standard for Safety

Household and Commercial
Batteries

BRITISH STANDARD

BS EN 60254-1:2005

Lead-acid traction batteries —

Part 1: General requirements and methods of test

The European Standard EN 60254-1:2005 has the status of a British Standard

ICS 29.220.20

Appendix III – Glossary of Terms

The purpose of this glossary is two-fold. It is to provide a reference to the terms used in this study and it is meant to provide an avenue to teach FIRST students interested in batteries from a more technical perspective.

Ampere: A unit of measure of electron current flow. 6.25×10^{18} electrons per second is one Ampere [11].

Ampere-hour (Ah): A measure of a battery's capacity. 1 Ah = 1 Amp flowing for 1 hour [12].

Anode: The electrode at which electrons are lost, i.e. the more positive electrode [12].

Cell: An individual electrochemical device composed of two electrodes of dissimilar metals and an electrolyte [11].

Cathode: The electrode at which electrons are gained, i.e. the more negative electrode [12].

CCA: The number of amperes a battery can supply at 0°F for 30 seconds to an end point voltage of 1.2V per cell. This rating is typically used with automotive SLI lead acid batteries [11].

Deep Cycle: A battery discharge consuming more than 80% of the battery's rated capacity [11].

Depth of Discharge (DOD) (%) – The percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity. A discharge to at least 80% DOD is referred to as a deep discharge [13].

Electrolyte Specific Gravity: The ratio of the weight of the electrolyte solution to the weight of an equal volume of pure water at a fixed temperature [12].

Electrolyte: Any acidic, basic or salt solution capable of conducting current. In a lead acid battery, the electrolyte is a dilute solution of sulfuric acid (H_2SO_4) in water (H_2O) [11].

Electron: A negatively charged particle that orbits the nucleus of an atom. When displaced from the orbit, the electron is free to flow as an electric current [11].

Electrode: A conductor of electricity which brings the current into, and leads it from the electrolyte [12].

Energy Density: The energy available from the battery per unit of volume, usually in Watt-Hours per Liter or Wh/L [12].

Internal Resistance: Expressed in ohms, the total DC resistance to the flow of current through the internal components (grids, active materials, separators, electrolyte, straps, inter-cell welds and terminals) of the battery [11]. This resistance can be measured with an instrument or calculated empirically with a known external resistor using Ohm's law.

Ion: An atom with more or fewer electrons than required to remain in equilibrium. Out of equilibrium, the atom becomes negatively or positively charged and can act as a current carrier. Ions, rather than electrons, are the current carriers of an electrolyte [11].

Ohm: A unit of electrical resistance. When one volt is applied across a resistor with one ohm of resistance, a current of one ampere will flow through the resistor [11].

Ohm's Law: An equation used in circuit analysis which states that the current flowing through a circuit is proportional to the voltage applied and is inversely proportional to the resistance of the circuit [11].

Open Circuit Voltage: The stabilized voltage at the battery terminals when no load is connected [11].

Peukert Equation: The Peukert equation is an empirical relationship describing the battery discharge capacity to discharge rate as follows [5][14]:

$$C_p = t * I^k$$

Where: C_p is the amp-hour capacity at a 1 Amp discharge rate.
I is the discharge current in Amperes.
t is the discharge time in hours.
k is the Peukert coefficient, typically 1.1 to 1.3 for Lead Acid Batteries

The relationship between C and C_p:

$$C_p = C^k$$

The Amp-Hour capacity is therefore:

$$I * t = C^{\left[1-\frac{1}{k}\right]}$$

Sealed Lead Acid Battery: A lead acid battery that is encapsulated with no venting or access to the electrolyte and internal components.

Self-Discharge: The intrinsic discharge of a battery in stasis over time when not in use [3].

SLI: An acronym for a Starting, Lighting and Ignition battery. An SLI battery's design is optimized for high rate cranking current delivery and is used in automotive applications [11]

Specific Energy: This is the energy available from the battery per unit of weight, and is usually expressed in Wh/kg [12].

State of Charge (SOC)(%) – An expression of the present battery capacity as a percentage of maximum capacity. SOC is generally calculated using current integration to determine the change in battery capacity over time [13].

Sulfation: - The formation of lead sulfate crystals in the battery plates. Over time, this sulfation can be difficult to reconvert to active material, leading to degraded battery capacity [15].

Traction Battery: A battery used in a "traction" device such as a vehicle, robot or other device [1].

Volt: A unit of electromotive force sufficient to carry one ampere of current through one ohm of resistance [11].

Watt: A unit of power. The product of the voltage (in volts) multiplied by the current (in amps) [11].

Watt hour (Wh): A unit of work. The product of power, expressed in watts, multiplied by the time, expressed in hours, over which the power is produced [11].

Wire Ampacity: The current that a conductor can carry continuously under the conditions of use without exceeding its temperature rating [16].

Wire Gauge: A term used to denote the physical size of a wire. In the United States, AWG is ubiquitous which stands for American Wire Gauge. It is a relative system for the designation of wire diameter. The higher the AWG number, the smaller the wire diameter [16].