Testing and Analysis of FIRST® Robotics Batteries

FIRST robotics batteries were tested and ranked to determine which batteries would provide maximum power for the robot in a competition. This need was identified by Team 2619, after a failure of the robot during a competition was due to an underperforming (although relatively new) battery. Sixteen batteries were analyzed and systematically ranked from first to worst using industry standards, so the team would know which batteries would perform the best during the competition season. Many veteran FIRST robotic teams gain a collection of batteries over time and it is often problematic to choose the best batteries to take to a competition. Three specific engineered test criteria were used to analyze battery performance. These were: 1 – high current drain time, 2 – low current drain time and 3 –internal resistance. An Excel spreadsheet was then generated for the final rankings and recommendations that were ultimately presented to the team. Finally, the top ten batteries were benchmarked using a dynamic battery loader that simulated a FIRST robotics competition. The tests conducted were derived from the following industry standards: IEC 60254-1 [1], SAE-J240 [2], SAE-J537 [3] and UL-2054 [9]. This study was designed and executed by the electrical sub team of FIRST (For Inspiration and Recognition of Science and Technology) Team 2619, "The Charge" which is the robotics club of Herbert Henry Dow High School (Midland Public Schools), Midland, Michigan, USA.

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Preface

In the 2014 competition season, our robot had a complete failure during a critical qualifying match while on the field. 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. *Is there a way to log battery performance while the robot is actually running?*

All of these challenges were met over the course of the last nine months and compiled in this document. The findings were both revelatory and elucidating. It has been a great learning experience for the team, the depth of our battery knowledge will undoubtedly help us in the immediate competition season and beyond. This report summarizes our findings and it is Team 2619's intent that these findings also help other FIRST teams.

March 2, 2015
FIRST Team 2619
"The Charge" – a Robotics Club of Herbert Henry Dow High School
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A copy of this report can be downloaded from the website above.

Executive Summary

When a robotics team is established, it faces numerous challenges that students and mentors have to anticipate and prepare for. However, as that team matures, and becomes comfortable with the systems put in place by FIRST, problems that seemed to be non-existent begin to surface and cause frustration.

The battery is one of the most essential components required to make a robot operational. For this reason, it is vital for teams to maintain quality in every battery they use and take to competitions. Over the years, FIRST Team 2619 has acquired many 12 volt batteries, of which their individual performance characteristics are indeterminate.

To rank all these batteries and institute a standard to which they will be held in the future, a series of tests were executed based on industry standards: discharge time to 11 volts at a 10 Amp load, discharge time to 10.5 volts at a 50 Amp load, and final internal resistance at 11 volts after a 10 Ampere load. These results were aggregated in an overall ranking. Here are the top ten batteries:

RANK	Battery ID	RANK	Battery ID
1	2015-1	**9**	2014-1-A
2	2015-2	**10**	2012-3
3	2015-3	**11**	2014-4
4	2013-1	**12**	2014-1-B
5	2012-4	**13**	2013-3
6	2014-2	**14**	2014-3
7	2013-2	**15**	2012-1
8	2012-5	**16**	2010-4

The rankings reveal that the newest batteries are not necessarily the best. This data allows the team to intelligently select batteries for competitions and general use. The top ten batteries from this list will be used during the 2015 competition season. More importantly, the methods learned in this study will put in place a precedent for future Team 2619 generations and other FIRST teams to follow to keep their battery collections organized and well managed.

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 ring. Many FIRST teams find out about the criticality of a battery in the worst possible way – with a poorly performing robot or even a total failure on the competition field during a match. A poorly performing battery may not only impede the speed and maneuverability of a robot, but it can also cause system-wide failure of the control system if the battery voltage falls below a critical threshold.

FIRST robotics teams acquire batteries through successive competition seasons as well as procure 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 becomes important to only bring the best batteries to the competition. This is especially true when teams have a multitude (even dozens) of batteries.

Figure 1 – Some of the Batteries Accrued by Team 2619

The problem at hand is how to rate a battery’s performance using both static and dynamic testing parameters. It would be ideal if each battery was placed in a robot and run through a competition while simultaneously measuring and recording its performance. 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 using three specific 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 "sees" 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 is 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 while in a competitive environment.

The device used to log this data was constructed and then tested during the fall of 2014 at the FIRST of the Great Lakes Bay Region "Bot-Bash" (an off-season event). This "battery logger" instrument provided the team details of what a FIRST battery must deliver during a match (see the figure on the next page). 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 is delivering 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. 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 nowhere near constant during this timeframe.

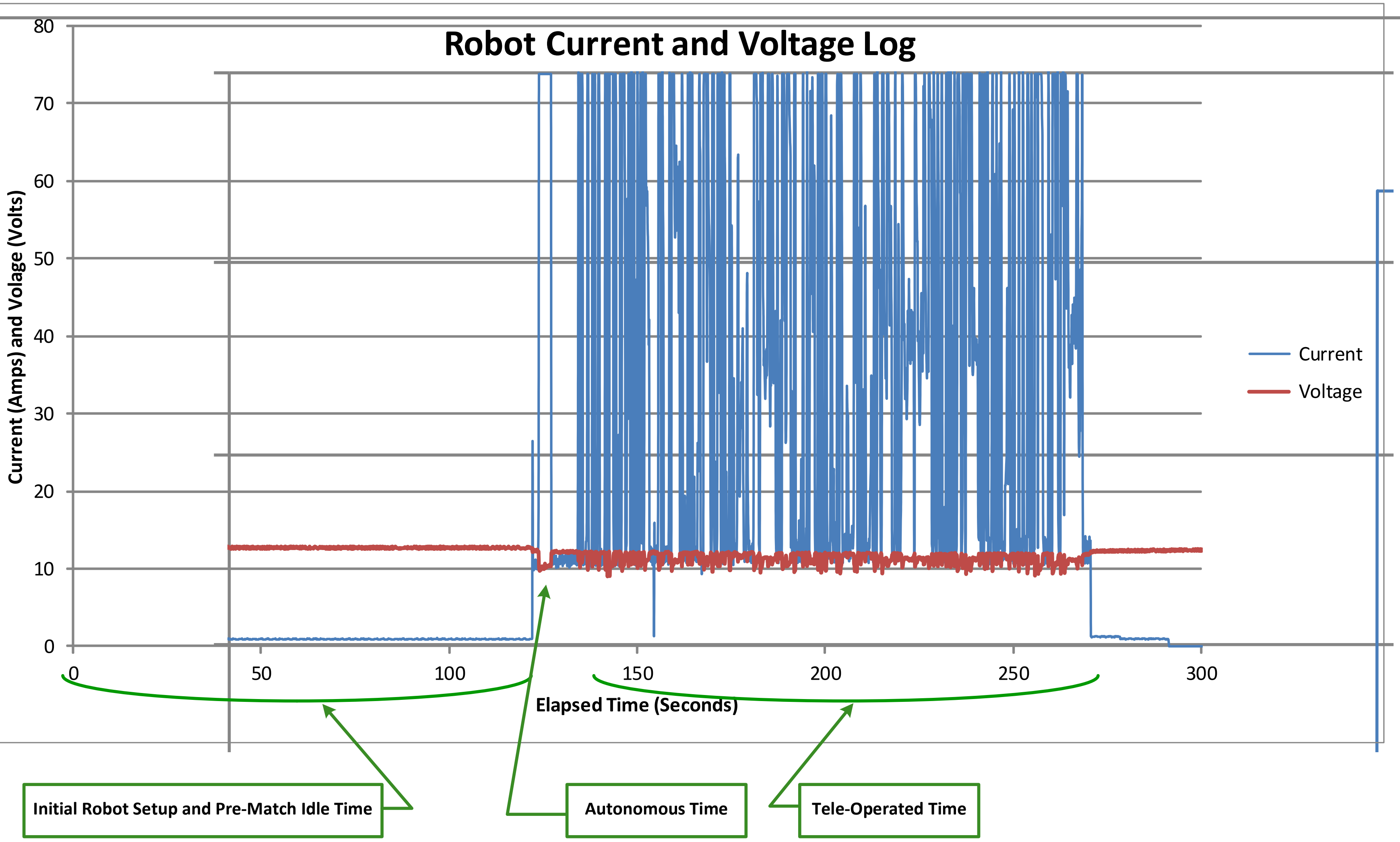


Figure 2 – Robot Voltage and Current Log During a Competition

Testing Methodology

Batteries are tested using several methods, each of which examines a specific area of battery performance. 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 depth of discharge it has experienced. A battery's internal resistance has a strong correlation to battery life with this regard 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.

High Current Discharge Test

The high current discharge test applies a 50 Ampere load to a fully charged battery. The load remains on the battery until the battery voltage drops to 10.50V or 1.75V per cell. The time that this takes is measured. In addition, the battery's parameters (internal resistance and open circuit voltage) are measured before and after the test. Finally, the battery's recharge time is measured. This test was derived from IEC 60254-1 section 5 [1]. This is depicted in the flowchart below.

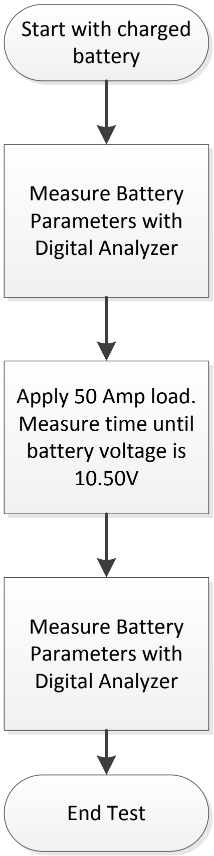
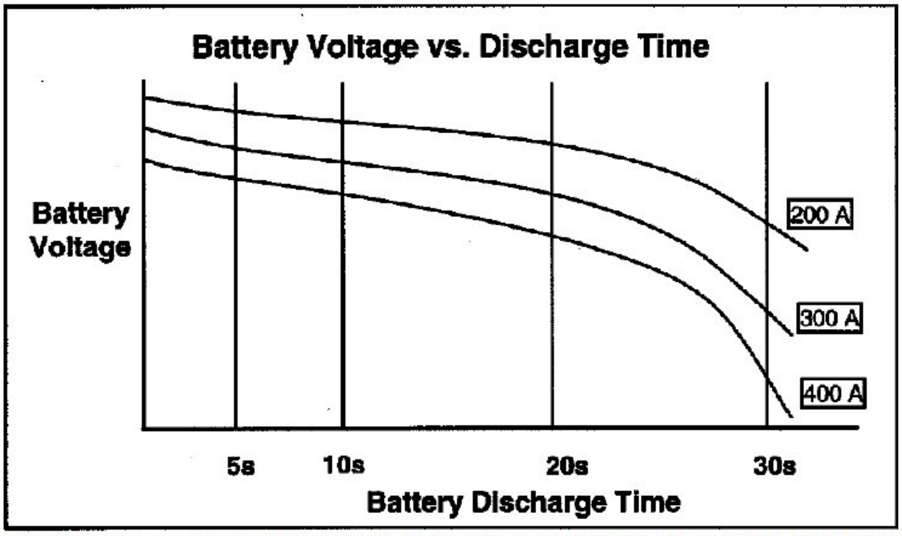


Figure 3 – High Current Discharge Test Flowchart (IEC 60254-1 [1]).

Low Current Discharge Test

The low current discharge test is identical to the high current discharge test, except that the load is 10 Amperes. It is anticipated that there will be less internal self-heating of the battery plates, and it will not simply be a linear function of a lower current drain over time in respect to the high current discharge test. This nonlinearity of battery discharge curves depending on load is highlighted in the SAE-J537 standard as shown in the figure below. The low current discharge test conducted in this study was derived from SAE-J240 revision 2002-10 section 3.4 [2].



EXAMPLE - BATTERY VOLTAGE VERSUS DISCHARGE TIME PLOT

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

Battery Internal Resistance Measurement

The parametric measurement of battery internal resistance was taken before and after both types of discharge tests. The post low current discharge internal resistance was used as a ranking criterion because it is an indication of the number of charge / discharge cycles a battery has experienced over its lifetime. The low current discharge internal resistance was selected over the high current internal resistance because there is minimal internal self-heating during the low current discharge test. Internal heating of the battery skews the results of the internal resistance measurement. 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.

Recipe Based Dynamic Load Test

The recipe based dynamic load test was used on the top ten batteries ranked from this study. The dynamic load recipe was derived from an actual robot mock competition which was logged using the battery logger instrument.

The purpose of the dynamic load tester is to eliminate variation in robot load seen by the battery during a competition. This instrument guarantees that the dynamic load placed on the battery under test is identical from battery to battery. It would be otherwise impossible to replicate the same competition environment consistently between batteries.

The battery current and voltage is logged during the dynamic load test using the battery logger in conjunction with the dynamic load tester. This data is then graphed using Excel. Please see Appendix I for the results of this test.

Data Interpretation and Battery Ranking

Batteries were ranked from first to last in three categories:

1. **High current discharge test - time to discharge**. This test provides a means to ascertain the battery's capacity under a severe load. The best performing battery would have the longest time to discharge in this test.

2. **Low current discharge test – time to discharge**. The battery's capacity is also tested here, except that a longer duration is anticipated. The best performing battery would have the longest time to discharge in this test.

3. **Low current discharge test – final internal resistance**. The final internal resistance of a battery is an indication of the sulfation present on its plates, given all other internal components equal (see the "Battery Basics" section of this report for the explanation of sulfation). The low current discharge internal resistance was chosen over the high current discharge internal resistance because there is far less internal heating under the smaller load conditions. This reduces the possibility of internal heat generation skewing the final internal resistance measurement. The best performing battery would have the smallest final internal resistance, indicating less sulfation.

For the 16 batteries tested in this study, each was ranked in the three categories above from 1 to 16. The final battery ranking is the average of the three criteria mentioned above. The top ten batteries were then recommended to the team for transport to the FIRST Robotics Competitions.

Finally, the top ten batteries were tested using the dynamic battery loader instrument to simulate a FIRST Robotics Competition.

Please see the Executive Summary for the battery ranking spreadsheet. All raw data is available in Appendix I.

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 high discharge and recipe based tests used equipment that created a substantial amount of heat. Some of the equipment had heat shielding, but personnel were also advised to be aware of the heat gradient generated by these particular tests with appropriate signage. There were no safety incidents during this study.

Figure 5 – Student with Batteries under Test.

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 [8], 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.

Figure 6 – Digital Battery Analyzer [8].

High Current Discharge Load Tester

The high current battery discharge test was comprised of several 250W wire-wound resistors mounted in parallel to create a nominal 50 Amp load. The resistors incorporated steel standoffs that provided separation between the potentially hot surface and the table. In addition, signage was created to alert personnel of the test in progress and high temperatures. A digital volt meter was used to monitor the battery voltage during the test.

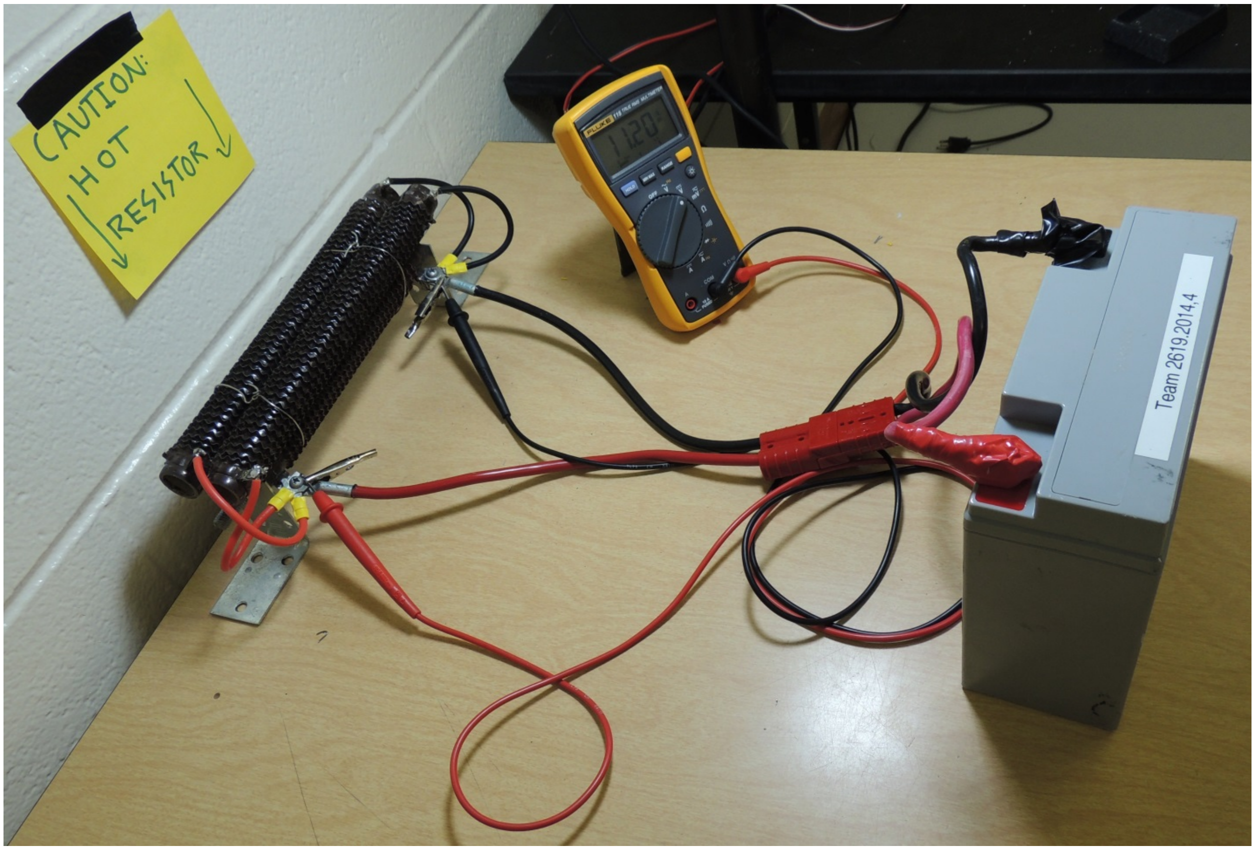


Figure 7 – High Current Discharge Load Test Setup

Low Current Discharge Load Tester

The low current battery discharge test was comprised of a single 250W wire-wound resistor that was connected to the battery using a standard FIRST Power-Pole connector. A digital volt meter was connected to the circuit to monitor the battery's voltage. A sign was posted to alert personnel of the hot testing apparatus.

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 can also be used in conjunction with the programmable dynamic battery loader to track battery performance during the recipe test. Since each recipe test is identical, batteries can be compared with each other to ascertain performance using the acquired data, displayed graphically on an Excel spreadsheet. Please see Appendix 3 for the Battery Logger's menu system and operation.

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 dynamic battery loader instrument, which is outlined in the next section.

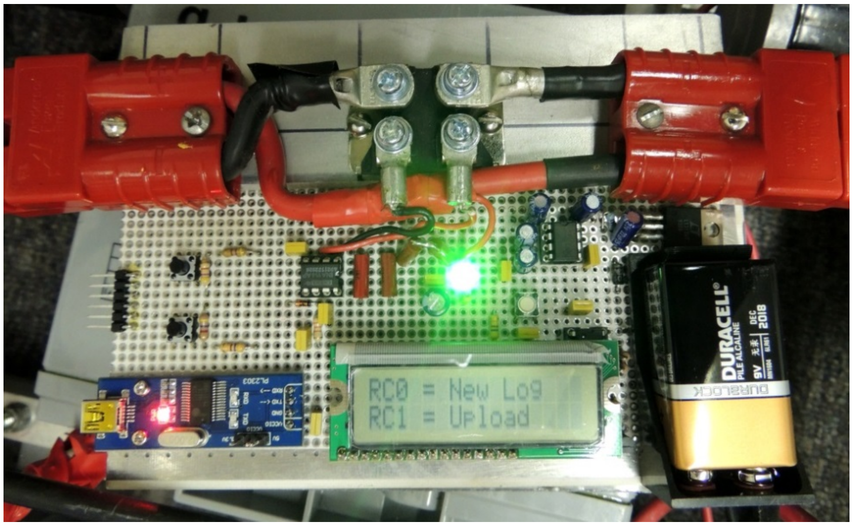


Figure 8 – Battery Logger

Programmable Dynamic Battery Loader

The programmable dynamic battery loader is a custom built instrument that can test a battery under a wide range of load values based on a pre-programmed recipe. The device can change the load on a 12V battery from zero to 100 Amps with better than 1% accuracy. The load can be varied within 100mS if necessary using Pulse Width Modulation (PWM). The purpose of this device is to provide an analog to a real robotics competition and test a series of batteries with the same exact dynamic loading conditions. The battery logger can be used in conjunction with this device to log the batteries dynamic performance. Please see Appendix 3 for the dynamic battery loader's menu system and operation.

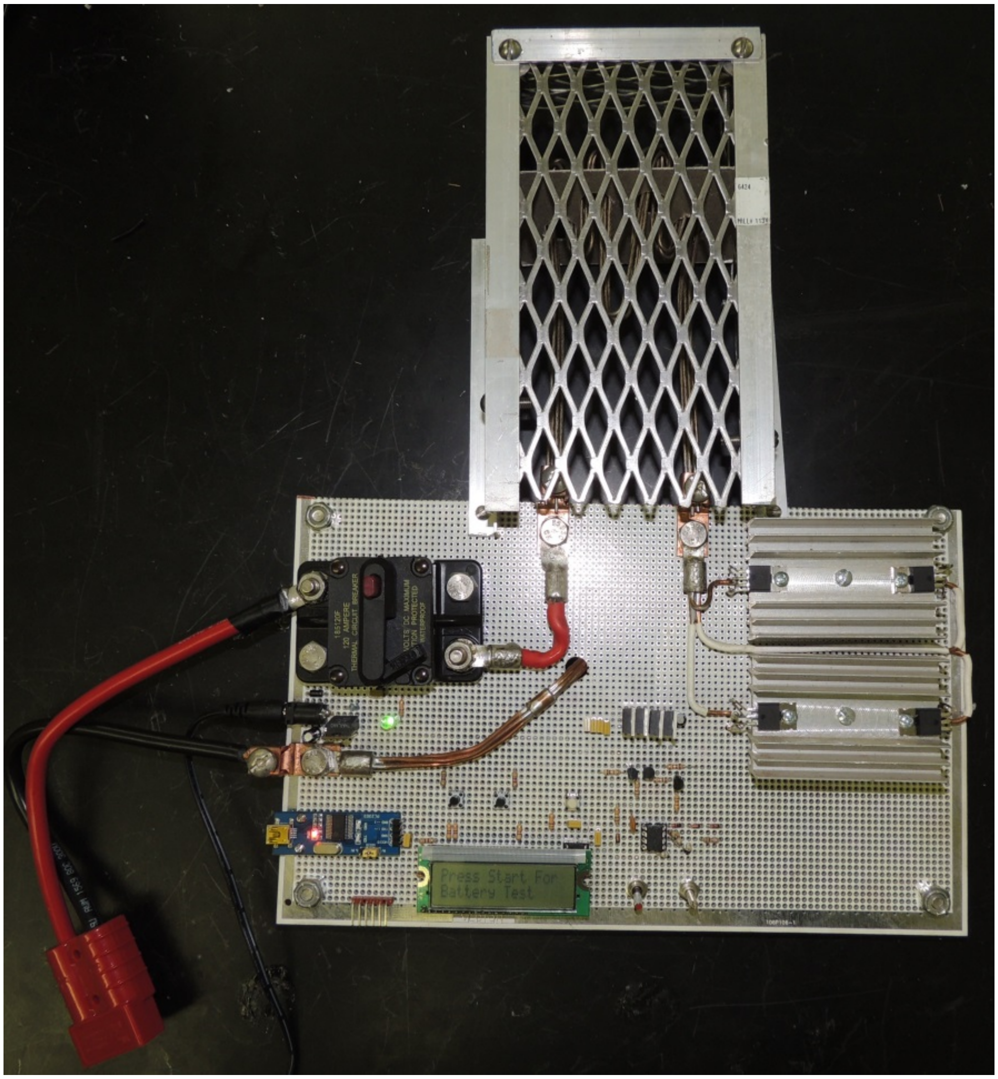


Figure 9 – Programmable Dynamic Battery Loader.

Battery Charger

The battery charger used in this study is the Black and Decker 2/4/6A Smart Battery Charger. It is the same battery charger used by Team 2619 since 2010. During the charging portion of the tests, the charger was placed on its highest charge rate and timed. 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” [9] 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).

The team has designed and fabricated a rolling battery cart that consists of six of these chargers and six battery slots. This battery cart is used in competitions and provides a portable effective platform for the team.

Figure 10 – Battery Charger

Figure 11 – 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 both rechargeable and 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 in non-electric and non-hybrid conventional automobiles. A sealed version of the Lead Acid battery is what is approved for use in FIRST Robots.

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 [4].

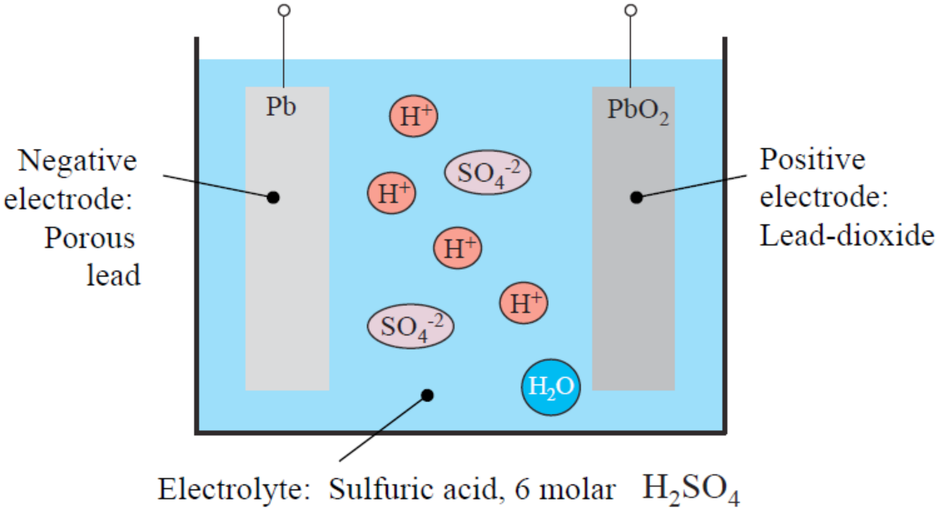


Figure 12 – Representation of a Lead Acid Cell [4].

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.

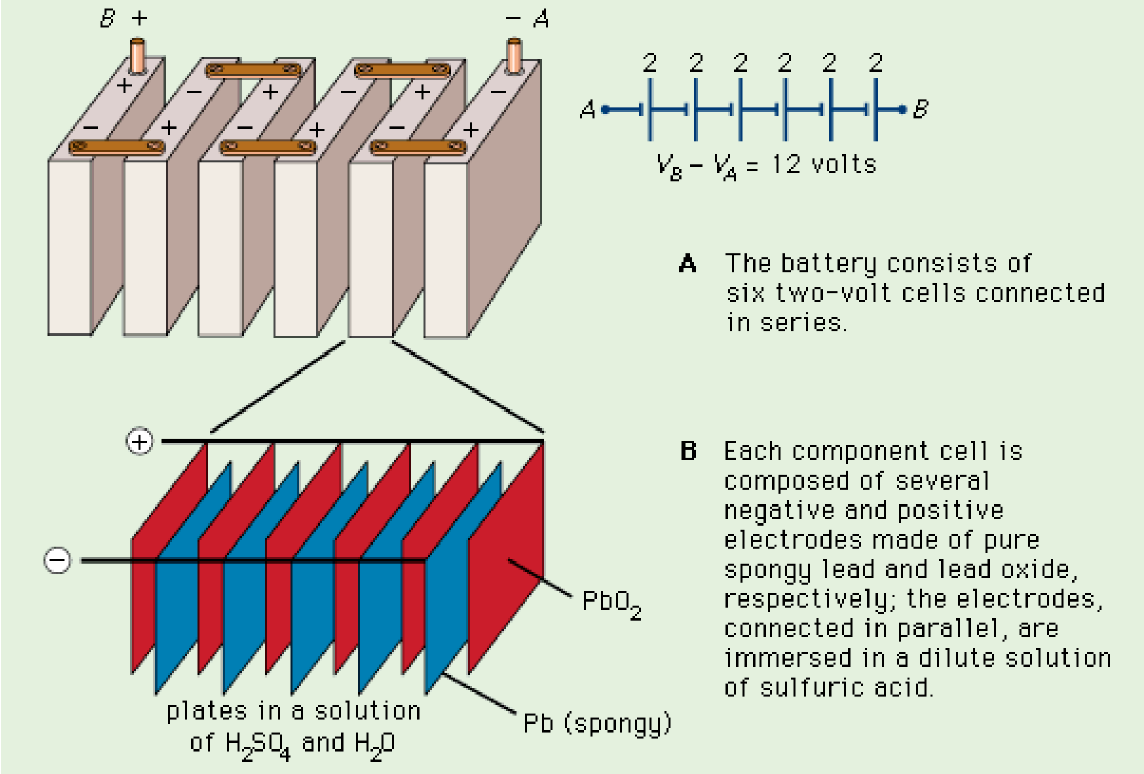


Figure 13 – Representation of a Lead Acid Battery [5].

Charging and Discharging

The flow of electrical current out of a battery's positive terminal through a load and returned 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 will reverse 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.

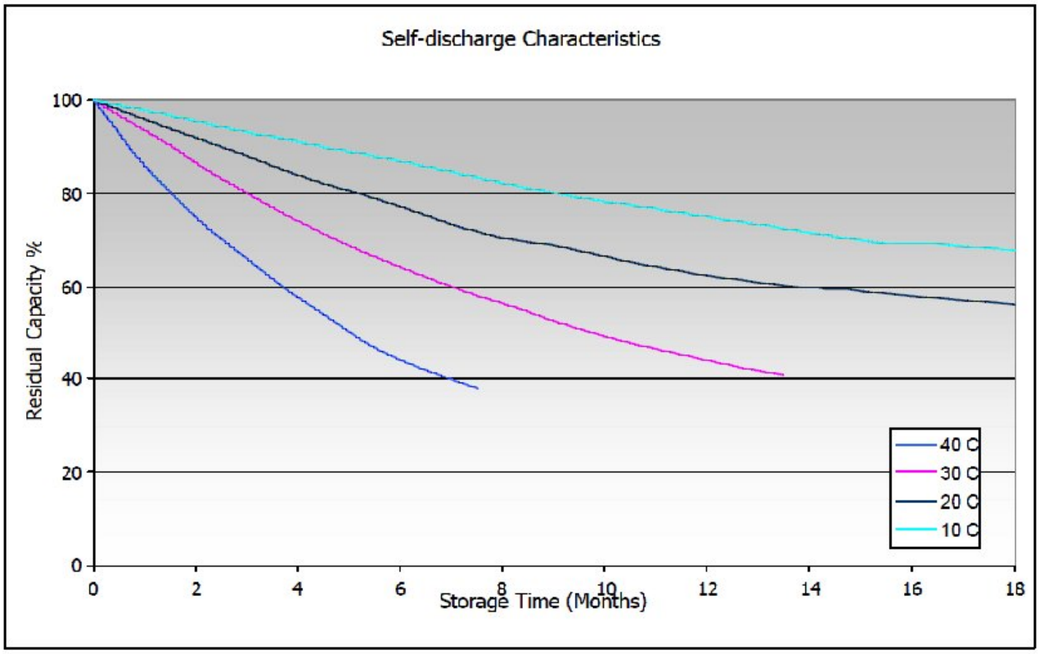


Figure 14 – Battery Self Discharge Characteristics [5].

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 from battery to battery, and is dependent on the battery's charge/discharge cycles, temperature as well as chemical effects inside the electrodes (such as sulfation). The fully charged FIRST robotics battery is specified to have an internal resistance of 11mΩ when new, at room temperature [6].

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 below:

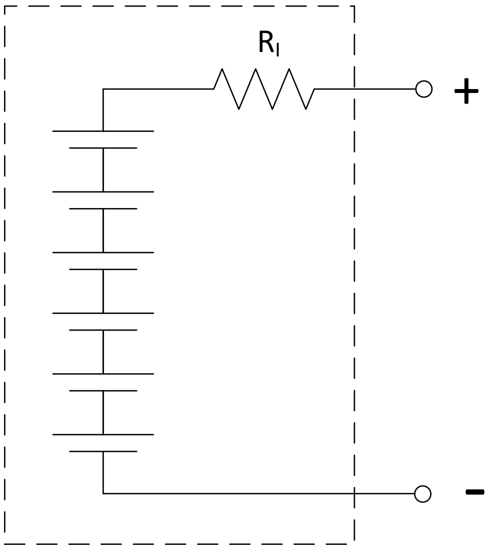


Figure 15 – Circuit Model of a Lead Acid Battery.

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 [4]. 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 16 – FIRST Robotics Typical Battery [6]

Specifications [6]:

- 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)

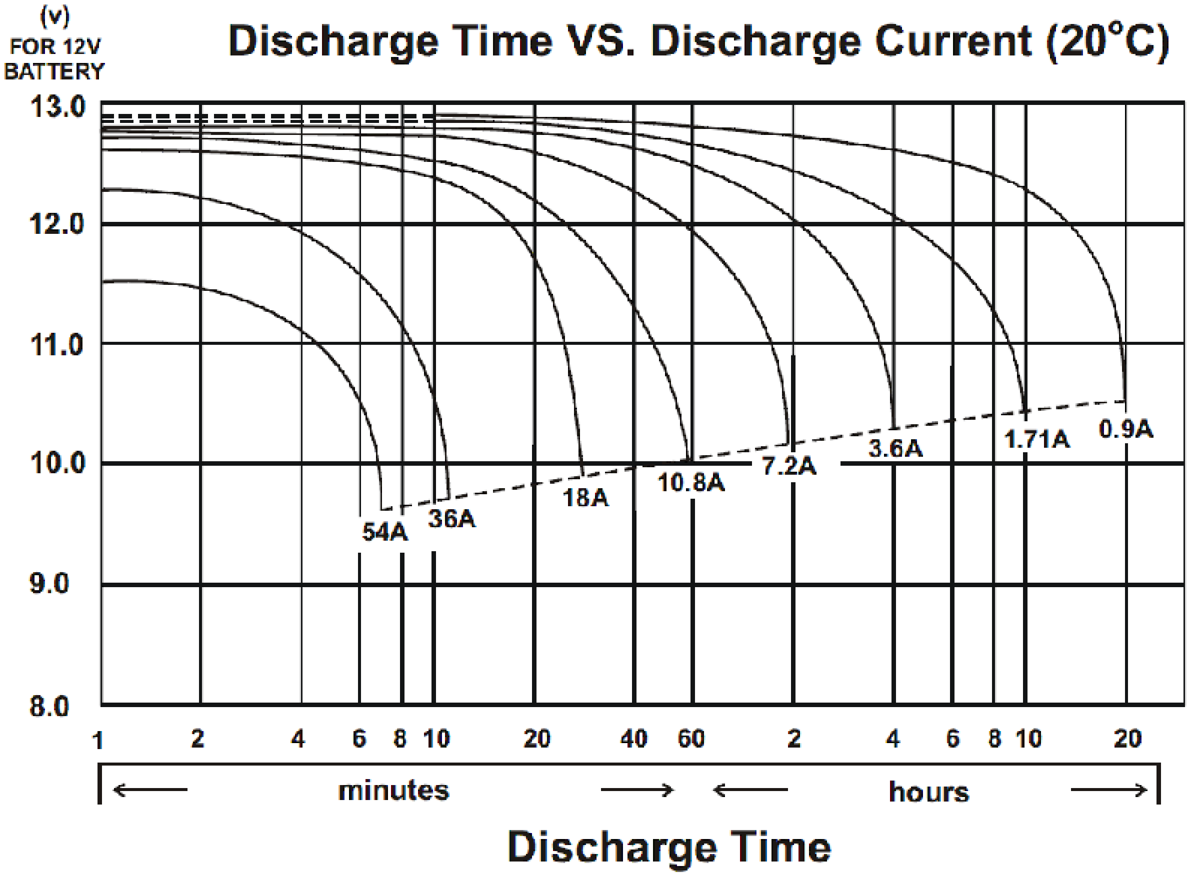


Figure 17 – MK ES17-12 Discharge Time vs. Discharge Current [7].

Conclusions

In this detailed analysis of Team 2619's FIRST robotics batteries, sixteen batteries were tested to determine their performance levels. Overall performance was based on ranks from three different test criteria: high current drain time, low current drain time, and internal resistance. After the final rankings were determined, the top ten batteries were deemed to have sufficient levels of execution to be used during competitions. The results show that batteries (from high to low ranking) 2015-1, 2015-2, 2015-3, 2013-1, 2012-4, 2014-2, 2013-2, 2012-5, 2014-4-A, and 2012-3 have the highest levels of performance and therefore will be taken to compete in the 2015 season. These results provide the team with a plethora of useful information. Before this analysis, it was assumed that the newest batteries would execute the highest level of performance. This statement was proven true to an extent–the three new batteries for 2015 were ranked in the first three places. However, these experiments have also shown that this is not always the case; for instance, battery 2014-3 was ranked fourteenth out of the sixteen even though it is only just a year old and battery 2013-1 was ranked fourth even though it is already two years old. This divergence from the commonly held belief that new batteries would perform the best in competitions is due to the fact that performance depends on the number of charge and discharge cycles, depth of discharges, vibration, temperature, and a wide variety of other external factors not necessarily dependent on battery age. Because each battery was tested in accordance with strict guidelines that ensured each was put through identical discharge and resistance experiments, variability in the results was significantly decreased. However, some errors may have occurred in the measurement of current drain using fixed resistor values while the battery voltage was decreasing. These errors could be reduced by using a variable load with a closed loop feedback system, which may improve the results of the investigation. In the future, the batteries could be re-tested after the competition season to explore how their use in competitions makes the batteries deviate from their original rankings. Further, other FIRST teams could carry out this analysis, and data from each could be compared to make broader conclusions about battery performance and age.

Study Participants

Main Authors

Satyajit Sarkar is currently a junior at H. H. Dow High School. He desires to pursue a degree in Computer Engineering starting in the fall of 2016. Satyajit has been a member of FIRST Team 2619 since 2013 serving as leader of the electrical sub-team. Satyajit is the webmaster of the Midland ACS and is the chair of its technology committee. He is also a member of the National Honor Society. In his spare time, Satyajit enjoys playing soccer, snowboarding, and travelling.

Jill Poliskey is currently a senior at H.H. Dow High School. She plans to attend either the University of Michigan or Michigan Technological University in the fall of 2015 to pursue a degree in Materials Science and Engineering. This is Jill's first year on FIRST Team 2619 and has served as a member of the electrical sub-team. Jill is a member of the National Honors Society and is president of Dow High School's Chemistry Club. She also enjoys playing the flute and piano, ballet dancing, and running cross-country.

Robert Most is a Professor of Electrical Engineering at Ferris State University. He has been a mentor of FIRST Team 2619 since 2009. In addition, he has served as a FIRST robot inspector, and is the faculty advisor to the FIRST Alumni student organization on campus. Bob received his BSEE from GMI (Kettering University) and his MSEE from Cornell University, specializing in analog circuit design and signal processing. He is a member of IEEE, ISA and ASEE. Bob enjoys tinkering with electronics, outdoor activities and playing guitar.

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PowerPoint Presentation to Team

Satyajit Sarkar	Student	***Michael Most***	Student
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http://www.harborfreight.com/digital-automotive-battery-analyzer-66892.html

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

Appendix I – Result Data

	Final Battery Ranking				
RANK	**Battery ID**	**Low Current Discharge Rank**	**Low Current Resistance Rank**	**High Current Discharge Rank**	**Sum of Ranks**
1	2015-1	1	2	1	4
2	2015-2	3	1	3	7
3	2015-3	2	6	2	10
4	2013-1	4	3	6	13
5	2012-4	5	5	4	14
6	2014-2	6	12	5	23
7	2013-2	9	4	12	25
8	2012-5	10	7	11	28
9	2014-1-A	12	9	9	30
10	2012-3	7	8	15	30
11	2014-4	8	15	10	33
12	2014-1-B	13	13	7	33
13	2013-3	11	11	14	36
14	2014-3	15	14	8	37
15	2012-1	14	10	13	37
16	2010-4	16	16	16	48

HIGH CURRENT TEST Nominal 50 Ampere Load (Battery Fully Charged)

Ranked by Longest Discharge Time

Rank	Battery ID	Initial Resistance	Initial Open Circuit Voltage	Load Test: Time to 10.50V Minutes	Final Resistance	Final Open Circuit Voltage	Post Test: Time to Re-Charge	Change in Resistance
1	2015-1	11.74	13.03	11.97	15.54	11.77	1 hr. 3 min.	3.80
2	2015-3	12.10	12.85	10.53	15.78	11.65	1hr. 41 min.	3.68
3	2015-2	16.60	13.48	10.25	20.51	11.94	1hr. 43 min.	3.91
4	2012-4	12.38	12.72	9.87	16.91	11.63	1 hr. 57 min.	4.53
5	2014-2	14.83	12.91	9.23	17.82	11.95	1 hr. 10 min.	2.99
6	2013-1	14.56	12.65	8.50	16.18	11.86	1 hr. 34 min.	1.62
7	2014-1-B	12.09	12.94	8.40	17.24	11.85	43 min.	5.15
8	2014-3	14.36	13.14	8.00	18.85	11.99	2 hr. 9 min.	4.49
9	2014-1-A	15.60	12.85	7.47	17.43	11.73	1 hr. 5 min.	1.83
10	2014-4	13.20	12.76	7.40	16.23	11.95	1 hr. 3 min.	3.03
11	2012-5	17.87	13.10	7.18	22.32	12.18	1 hr. 23 min.	4.45
12	2013-2	13.42	12.44	7.03	17.19	11.77	1 hr. 10 min.	3.77
13	2012-1	13.69	12.59	6.87	18.12	11.73	56 min.	4.43
14	2013-3	16.38	12.61	6.57	19.19	11.73	39 min.	2.81
15	2012-3	14.71	12.93	4.73	23.06	12.05	1 hr. 14 min.	8.35
16	2010-4	18.09	12.56	1.33	22.18	12.00	25 min.	4.09

LOW CURRENT TEST Nominal 10 Ampere Load (Battery Fully Charged)

Ranked by Longest Discharge Time

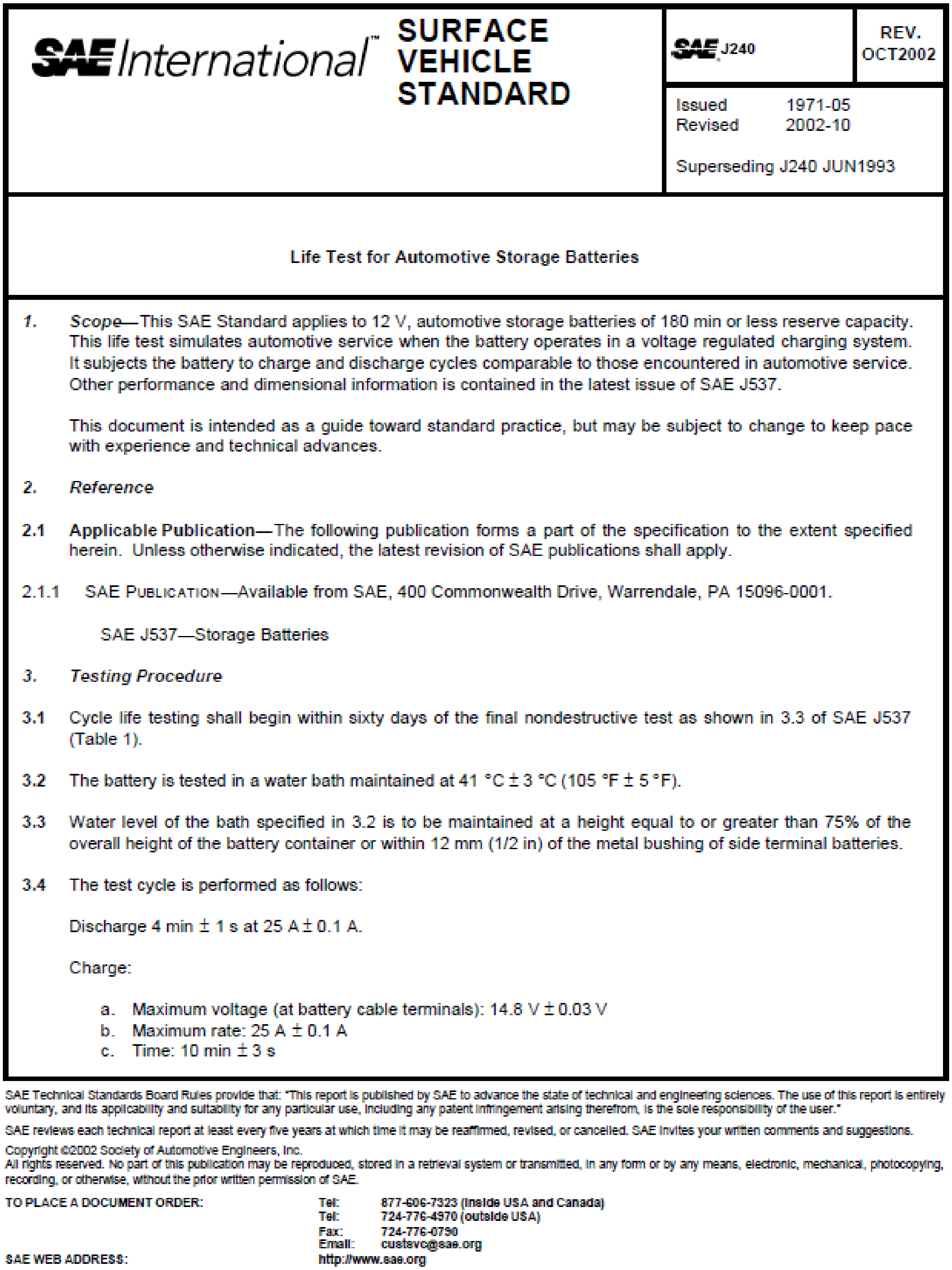
Rank	Battery ID	Initial Resistance	Initial Open Circuit Voltage	Load Test: Time to 11.00V Minutes	Final Resistance	Final Open Circuit Voltage	Change in Resistance
1	2015-1	12.97	13.60	67.20	21.99	11.66	9.02
2	2015-3	17.44	12.80	64.10	24.41	11.54	6.97
3	2015-2	11.38	13.18	55.17	20.50	11.55	9.12
4	2013-1	14.49	13.06	55.04	22.63	11.60	8.14
5	2012-4	13.83	13.14	52.20	24.01	11.62	10.18
6	2014-2	11.32	13.20	48.30	30.43	11.66	19.11
7	2012-3	18.34	13.71	46.67	24.76	11.46	6.42
8	2014-4	11.99	12.93	46.00	35.40	11.69	23.41
9	2013-2	13.75	12.89	44.42	22.83	11.65	9.08
10	2012-5	13.00	12.98	44.10	24.56	11.79	11.56
11	2013-3	15.94	13.10	43.53	27.90	11.81	11.96
12	2014-1-A	12.29	12.55	39.92	24.88	11.49	12.59
13	2014-1-B	13.15	12.92	39.40	31.14	11.75	17.99
14	2012-1	14.37	12.83	39.00	25.71	11.62	11.34
15	2014-3	20.89	12.75	31.50	34.86	11.60	13.97
16	2010-4	15.81	12.85	22.25	37.76	11.85	21.95

LOW CURRENT TEST Nominal 10 Ampere Load (Battery Fully Charged)

Ranked by Final Internal Resistance

Rank	Battery ID	Initial Resistance	Initial Open Circuit Voltage	Load Test: Time to 11.00V Minutes	Final Resistance	Final Open Circuit Voltage	Change in Resistance
1	2015-2	11.38	13.18	55.17	20.50	11.55	9.12
2	2015-1	12.97	13.60	67.20	21.99	11.66	9.02
3	2013-1	14.49	13.06	55.04	22.63	11.60	8.14
4	2013-2	13.75	12.89	44.42	22.83	11.65	9.08
5	2012-4	13.83	13.14	52.20	24.01	11.62	10.18
6	2015-3	17.44	12.80	64.10	24.41	11.54	6.97
7	2012-5	13.00	12.98	44.10	24.56	11.79	11.56
8	2012-3	18.34	13.71	46.67	24.76	11.46	6.42
9	2014-1-A	12.29	12.55	39.92	24.88	11.49	12.59
10	2012-1	14.37	12.83	39.00	25.71	11.62	11.34
11	2013-3	15.94	13.10	43.53	27.90	11.81	11.96
12	2014-2	11.32	13.20	48.30	30.43	11.66	19.11
13	2014-1-B	13.15	12.92	39.40	31.14	11.75	17.99
14	2014-3	20.89	12.75	31.50	34.86	11.60	13.97
15	2014-4	11.99	12.93	46.00	35.40	11.69	23.41
16	2010-4	15.81	12.85	22.25	37.76	11.85	21.95

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

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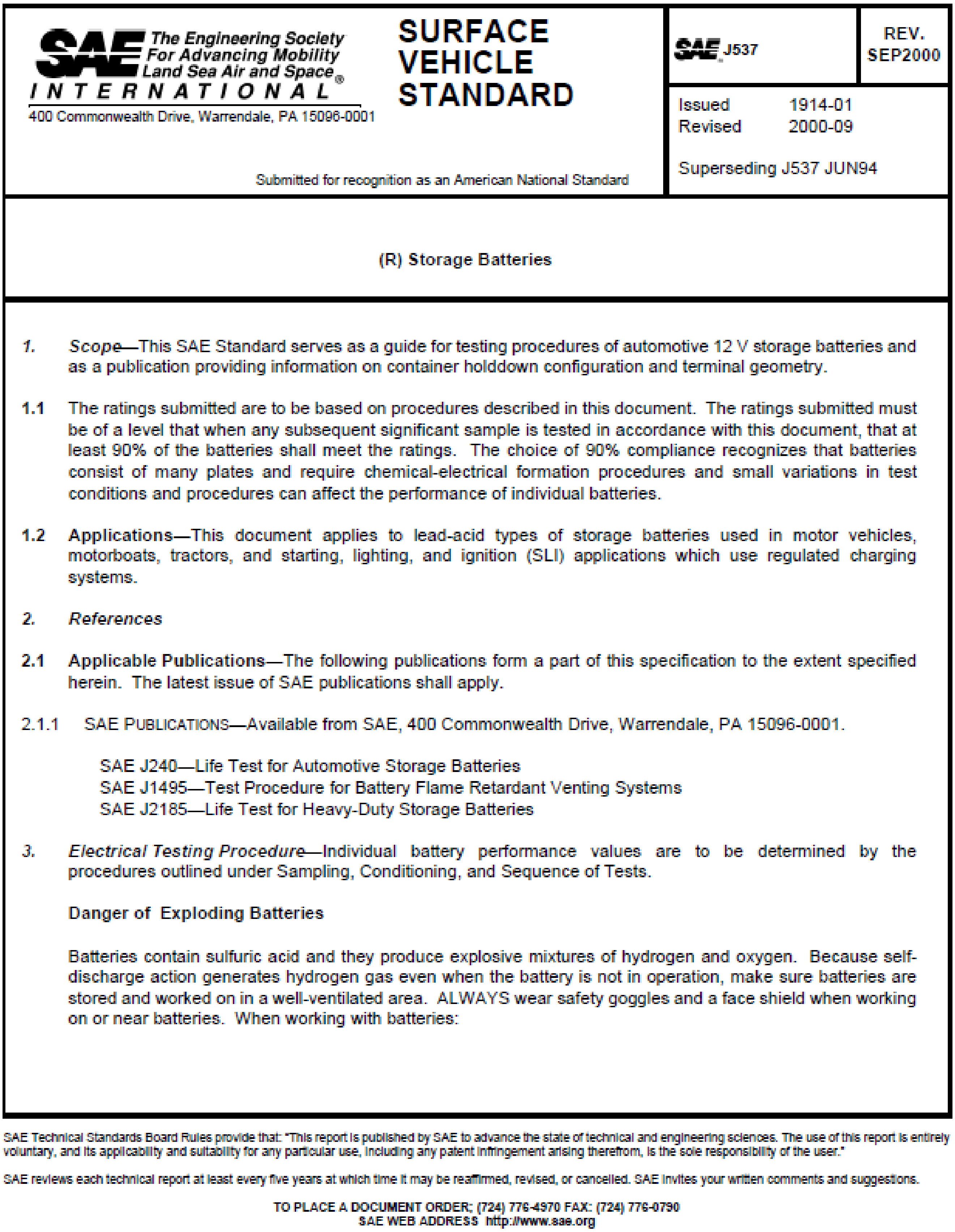
SAE WEB ADDRESS: http://www.sae.org



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.

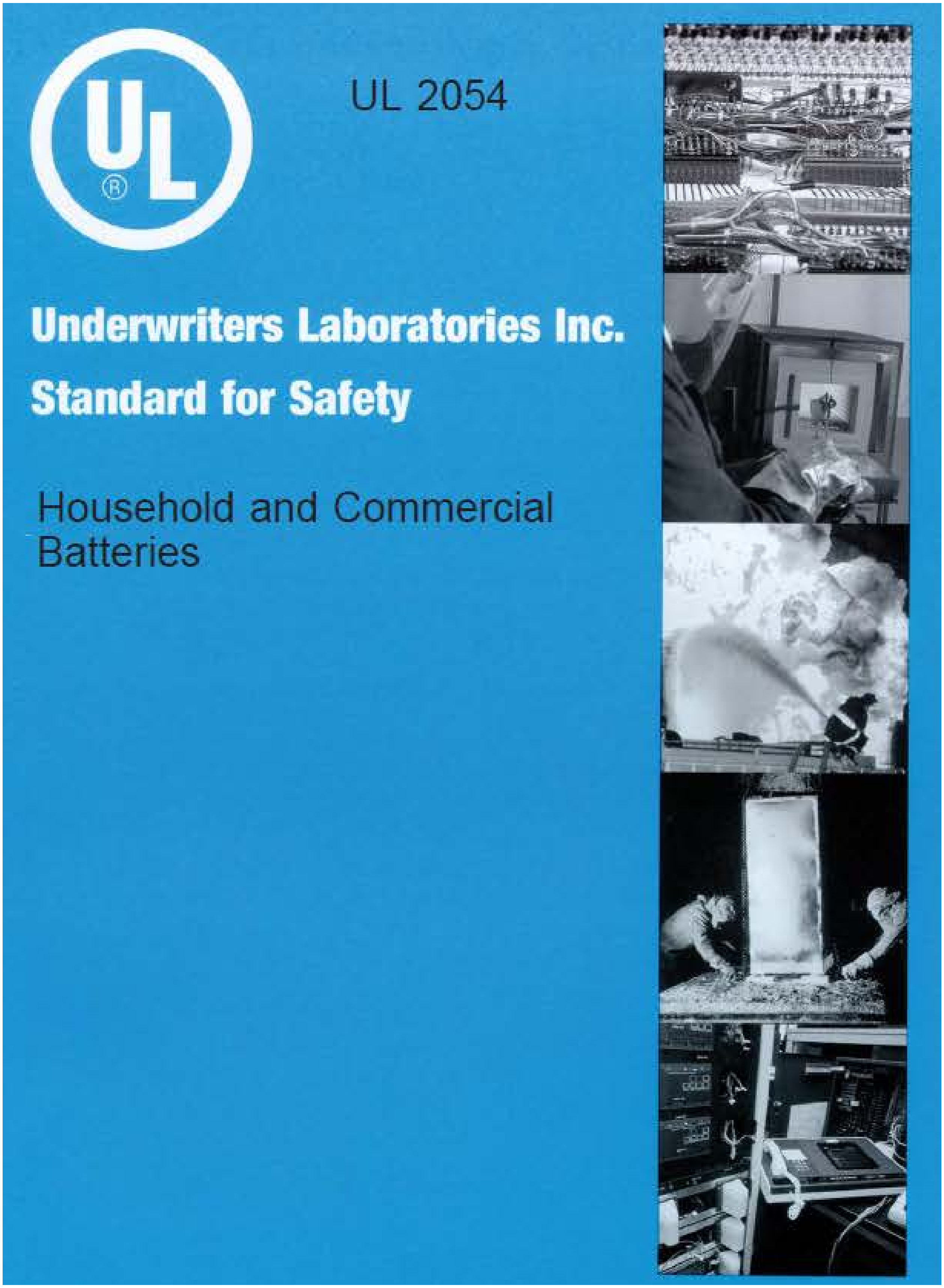
SAE J240—Life Test for Automotive Storage Batteries
SAE J1495—Test Procedure for Battery Flame Retardant Venting Systems
SAE J2185—Life Test for Heavy-Duty Storage Batteries

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:

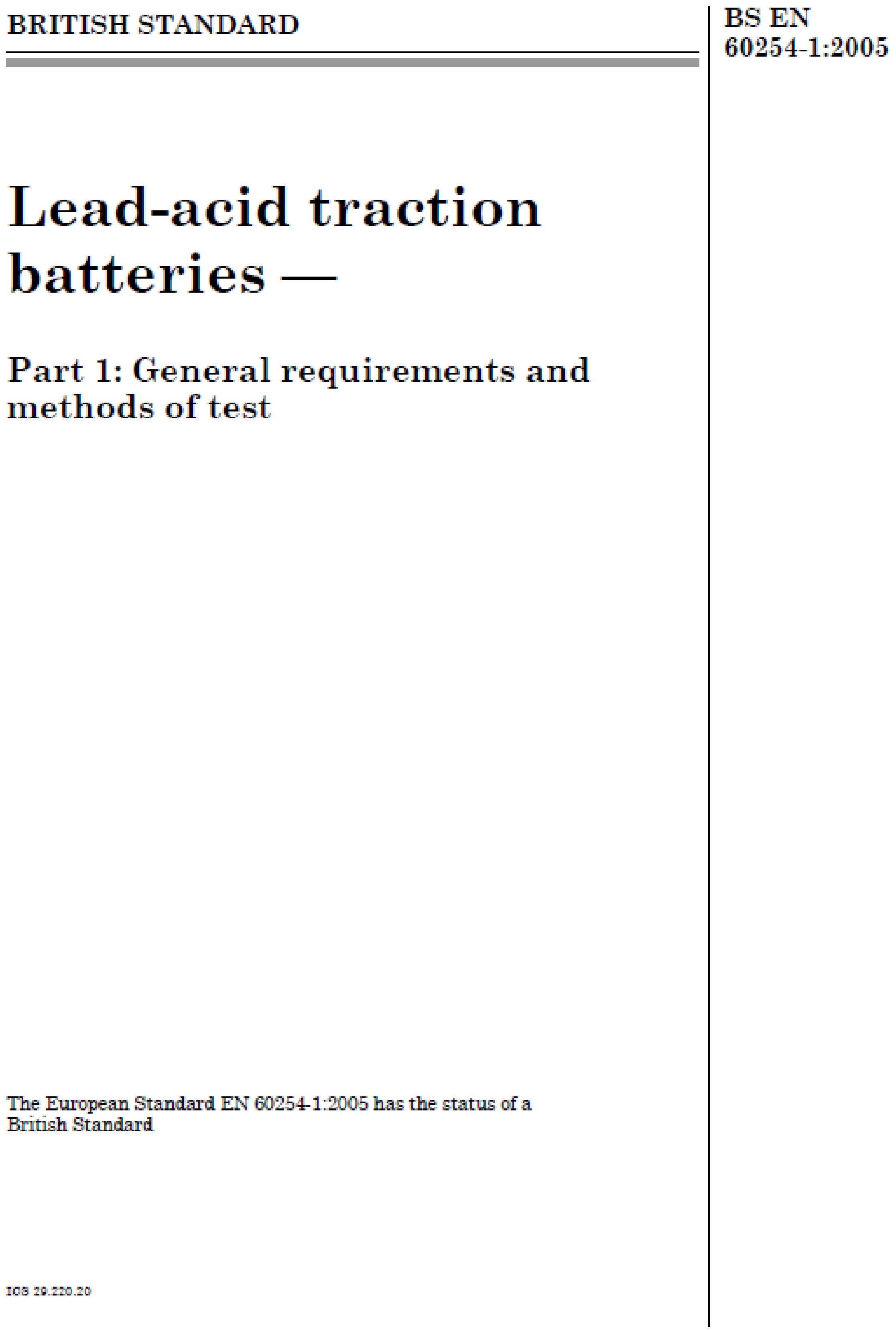
TO PLACE A DOCUMENT ORDER; (724) 776-4970 FAX: (724) 776-0790
SAE WEB ADDRESS http://www.sae.org



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 –Custom Instrument Details

Two custom made instruments were used to aid in this study. The first is the battery logger which can store up to 10 minutes worth of battery voltage and current at 10 samples per second. It is capable of up to 100 Amps of current and can be placed in the robot or used in conjunction with the dynamic battery loader. Its logged data is then uploaded via a USB cable to an Excel spreadsheet for analysis. See Figure 8 for a picture of the battery logger.

The dynamic battery loader runs a recipe based load test on a battery, or can be manually adjusted to provide a load of up to 100 Amps. In future iterations, it will be capable of downloading a battery log from the logger and use that data to create a “dynamic load copy” of a real robot run. For this study, a simulated robot run was used to verify its operation. The flowchart below depicts the recipe that was used.

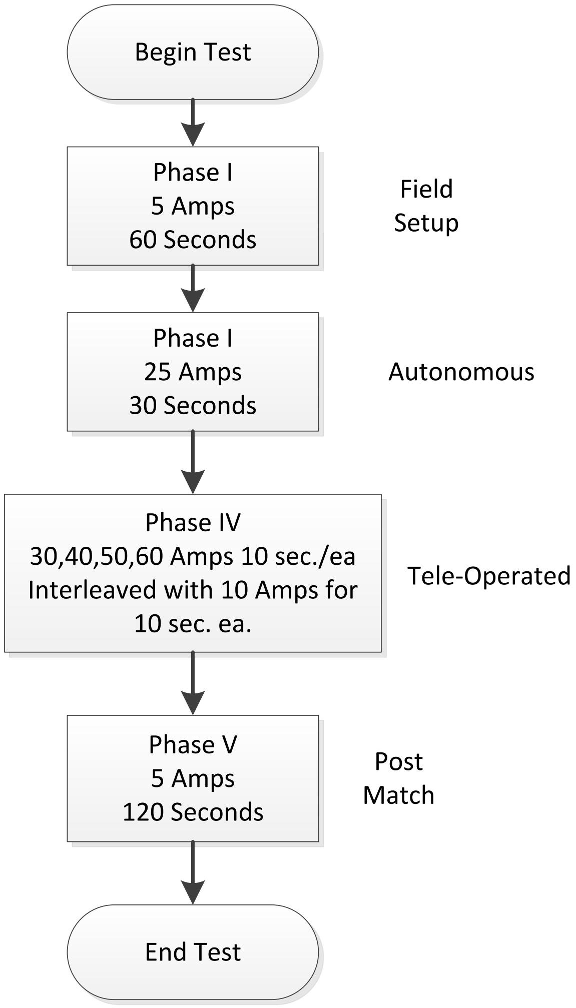


Figure 18 – Flowchart of the Dynamic Battery Loader Recipe

The dynamic battery loader was implemented on the top ten batteries from this study. A typical test setup is shown in the figure below.

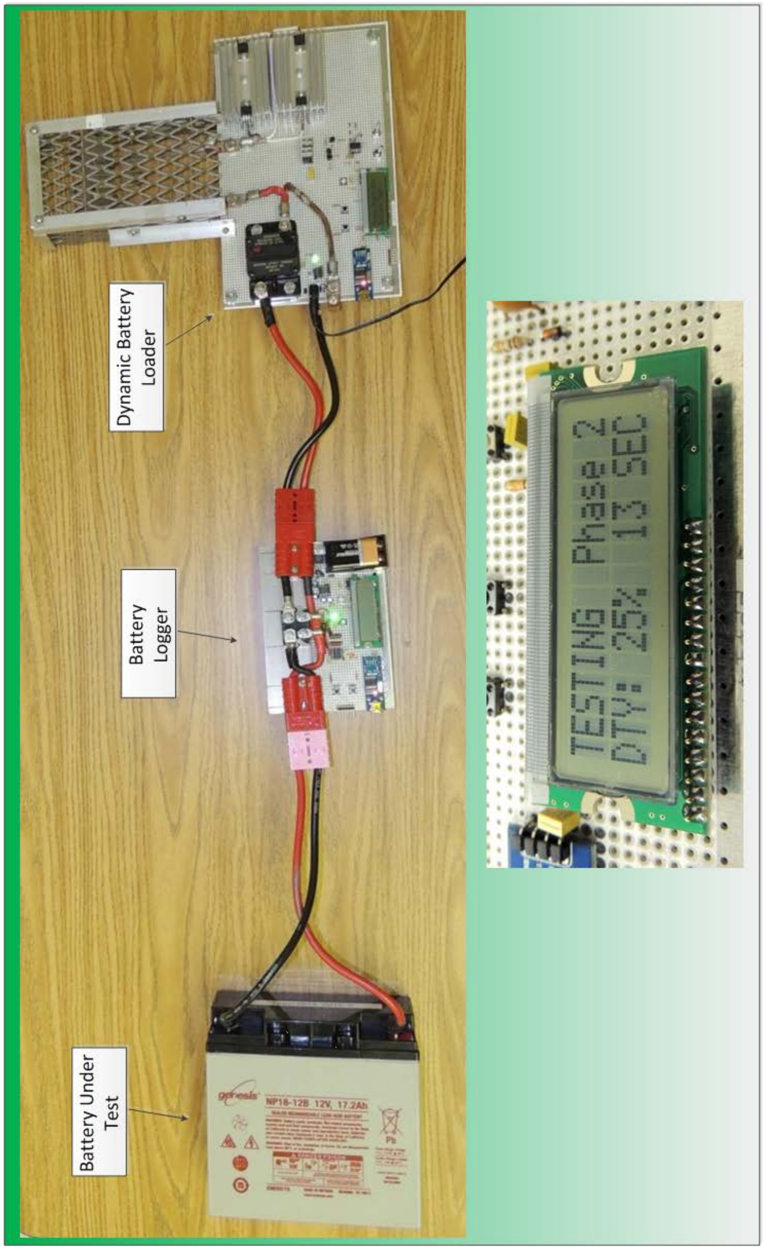
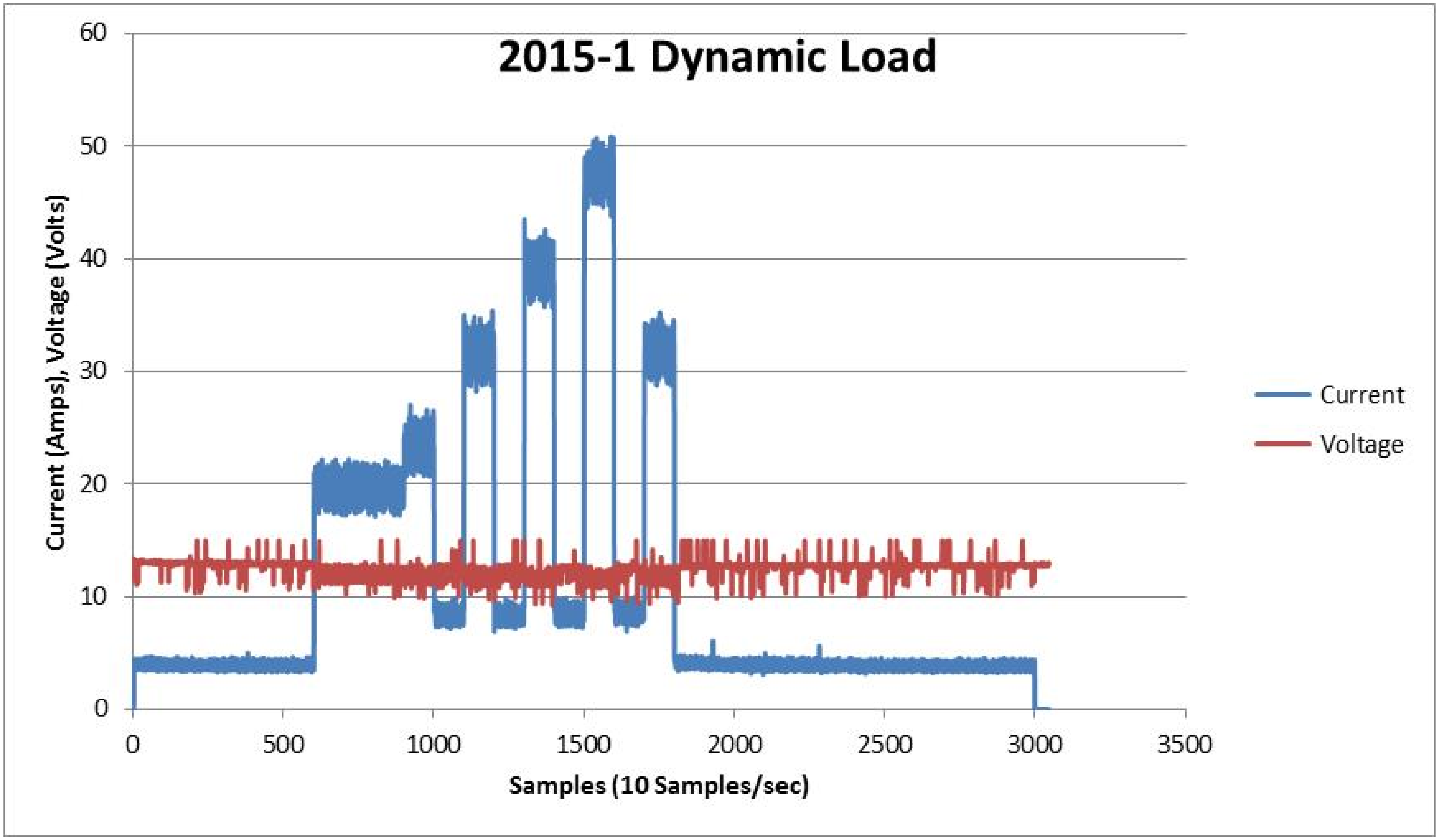
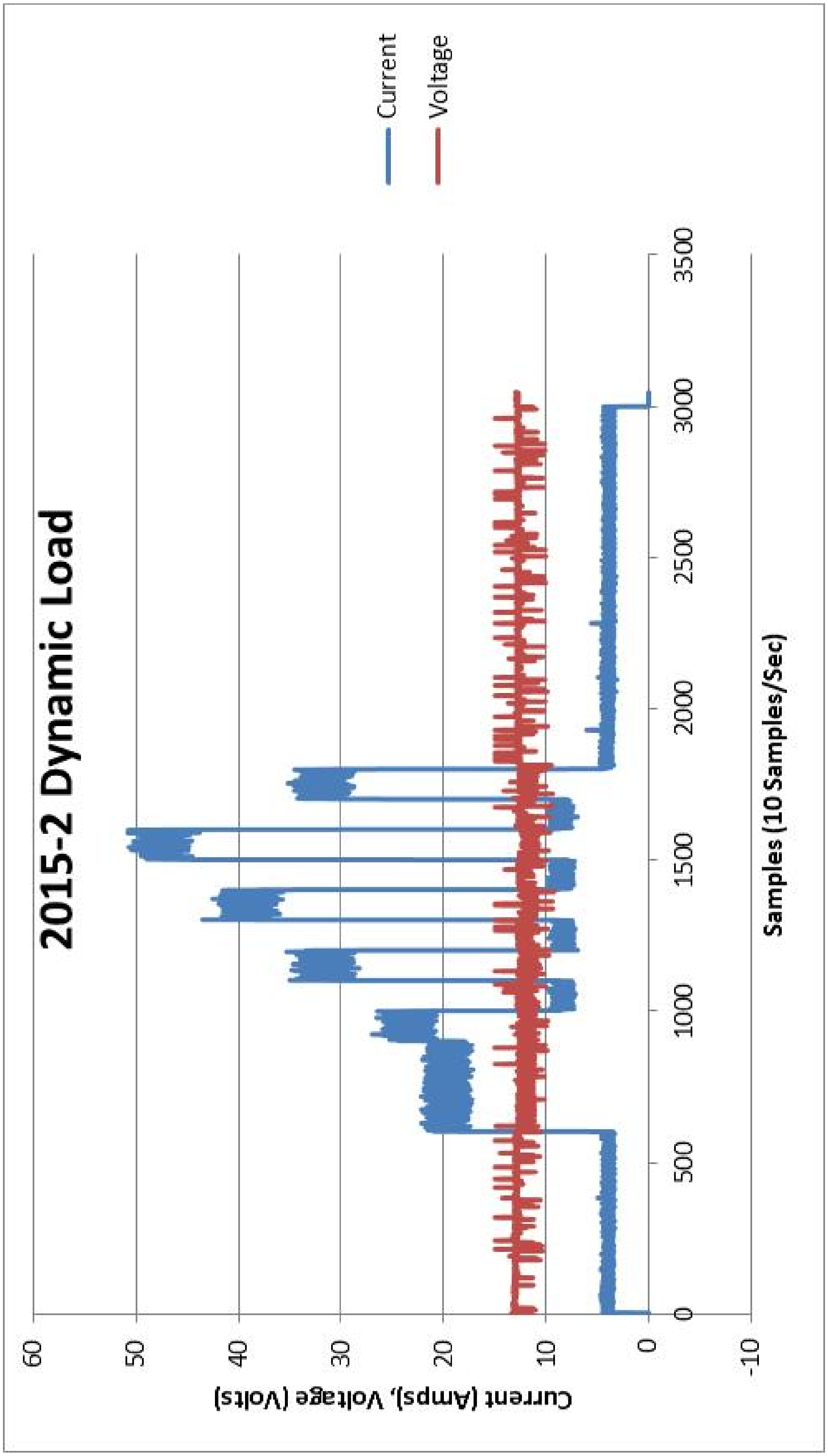


Figure 19 – Battery Logger and Dynamic Battery Loader used together with inset photo of typical menu prompt on the LCD display.

The next two pages include the logging output uploaded to Excel for two of the ten batteries tested. This verifies the application of the Logger / Dynamic Loader configuration and will be used in the future to mimic actual runs of the robot.


2015-1 Dynamic Load
Current (Amps), Voltage (Volts)
0
10
20
30
40
50
60
Samples (10 Samples/sec)
0
500
1000
1500
2000
2500
3000
3500
Current
Voltage


2015-2 Dynamic Load
Current (Amps), Voltage (Volts)
60
50
40
30
20
10
0
-10
0
500
1000
1500
2000
2500
3000
3500
Samples (10 Samples/Sec)
Current
Voltage

Appendix IV – 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 [10].

Ampere-hour (Ah): A measure of a battery's capacity. 1 Ah = 1 Amp flowing for 1 hour [11].

Anode: The electrode at which electrons are lost, i.e. the more positive electrode [11].

Cell: An individual electrochemical device composed of two electrodes of dissimilar metals and an electrolyte [10].

Cathode: The electrode at which electrons are gained, i.e. the more negative electrode [11].

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 [10].

Deep Cycle: A battery discharge consuming more than 80% of the battery's rated capacity [10].

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 [12].

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 [11].

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) [10].

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 [10].

Electrode: A conductor of electricity which brings the current into, and leads it from the electrolyte [11].

Energy Density: The energy available from the battery per unit of volume, usually in Watt-Hours per Liter or Wh/L [11].

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 [10]. 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 [10].

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 [10].

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 [10].

Open Circuit Voltage: The stabilized voltage at the battery terminals when no load is connected [10].

Peukert Equation: The Peukert equation is an empirical relationship describing the battery discharge capacity to discharge rate as follows [4][13]:

$$C_p = t * I^k$$

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 [10]

Specific Energy: This is the energy available from the battery per unit of weight, and is usually expressed in Wh/kg [11].

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 [12].

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 [14].

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 [10].

Watt: A unit of power. The product of the voltage (in volts) multiplied by the current (in amps) [10].

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 [10].

Wire Ampacity: The current that a conductor can carry continuously under the conditions of use without exceeding its temperature rating [15].

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 [15].