Life Cycle Testing of Series Battery Strings with Individual Battery Equalizers

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ABSTRACT

This paper presents experimental verification of the impact of individual battery equalization on battery life and performance. A study of two battery systems, one equipped with PowerCheq equalizers, a new battery equalization device, and one without, was conducted over 450 charge and discharge cycles simulating an electric scooter drive routine. The data clearly shows that the batteries equipped with the PowerCheq devices (individual battery equalizers) outperformed those with no equalization as well as those employing string equalization. In fact, the battery without the equalizers reached its end of life (80% of initial capacity) after 140 drive cycles while the one with the equalizers lasted more than 450 drive cycles, thus tripling battery life. The use of modular, real-time individual battery equalizers allows batteries to stay equalized during charge as well as discharge cycles thus improving battery life and longevity.

I. Introduction

Series battery strings are used as the main power source in many cyclic and stationary applications. In almost all applications, the battery string is treated as a single unit and all batteries within the string are assumed to be exactly the same. This is far from reality. Differences in cell chemistry and normal differences during repeated cycles of cell charge and discharge lead to large non-uniformities in cell charge levels and correspondingly dissimilarities between individual cells. In fact, dissimilarities between individual cells/modules can be attributed to many factors including:

- Normal (chemical) differences between battery cells/modules
- Differences in charge acceptance rates
- Differences in discharge capacities
- Differences in grid deterioration rates

These differences give rise to cell imbalances, which lead to reduced string capacity and reduced life. As a result, efforts to reduce cell imbalances will positively impact battery life and performance.

Almost all series battery strings are charged serially using a single charger. This often leads to improper charging of some cells within the string, namely undercharging and/or overcharging. Undercharging of batteries leads to reduced cell capacities and potential sulfation, which is the formation of large crystals of lead sulfate. Overcharging, on the other hand, leads to the loss of lead (loss of life), the loss of electrolyte, and a potential thermal runaway. Figure 1 shows an example of a four battery string being charged by a single charger and the potential for having both undercharged and overcharged cells. Achieving proper charging on a per cell/module level for series strings is quite challenging.

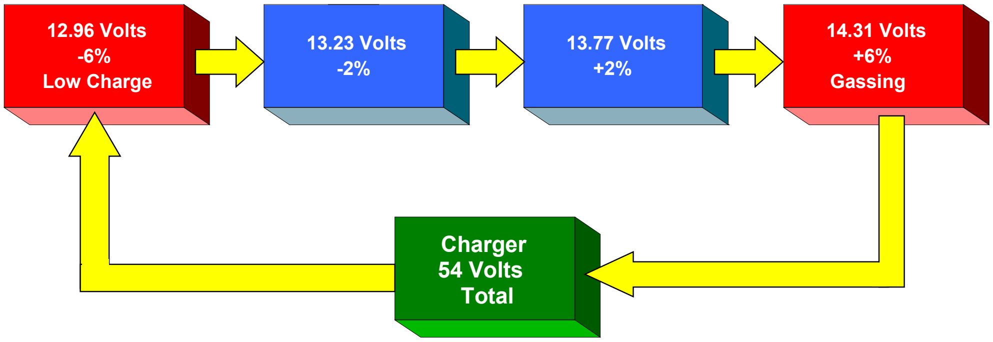

Figure 1: Serial charging of a 4-battery string

II. String Equalization

One technique that has been widely used to overcome improper charging in series battery strings is string equalization. As series string chargers are unable to distinguish or address dissimilarities between individual cells, string equalization attempts to solve part of the problem through charging up undercharged cells.

String equalization is normally achieved by applying an extended period of “float charge”. The main goal is to allow undercharged cells to develop full state of charge through the extended overcharge period. Although this technique addresses the issue of undercharged cells within a string, it often causes overcharging of good cells while masking high resistance cells. A false sense of security is often created when the float current level is at a low level. In reality, that low charge current may well be high enough to cause serious damage to healthy cells. This leads to reduced battery life and increased operating cost.

The effectiveness of string equalization in achieving cell balancing has been investigated by many. The results of these studies clearly show that string equalization can easily cause some cells to be overcharged forcing them into gassing while others remain undercharged. Even after the termination of equalization charging, many cells remain undercharged. The studies verify the inability of string equalization to ensure that all cells within the string are equally charged. In addition, infrequent or very frequent string equalization leads to battery degradation due to either sulfation or overcharging or gassing of good cells.

III. Impact of Equalization Voltage

The level of the equalization voltage greatly impacts the life of the battery cells. During charging, when the charging current applied to the cell reaches a certain level, the positive and negative plates begin to become polarized relative to their open circuit potentials. The polarization does not occur immediately because the initial current goes to replace the current lost to self-discharge. These polarizations cause the voltage of the cell to rise such that it is equal to the cell's open circuit voltage (OCV) plus the positive and negative polarization levels. In VRLA, at low charging currents, the positive plate polarization (PPP) is more dominant than the negative plate polarization. Figure 2 shows the cell polarization of a VRLA battery.

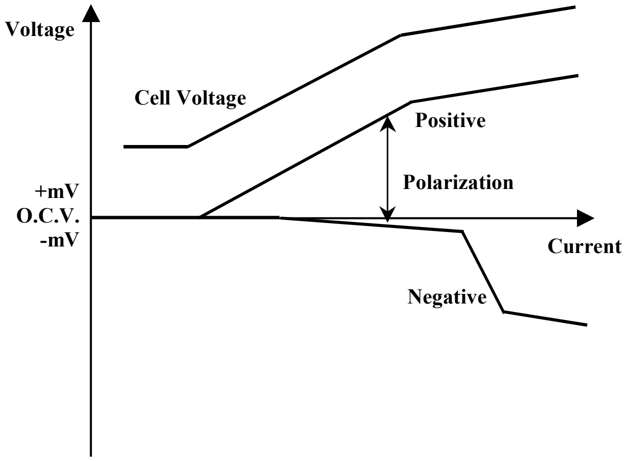

Figure 2: Cell polarization in a VRLA battery

The discussion of positive plate polarization (PPP) is necessary to understand the effects of equalization/float voltage on battery life. The reason that PPP is important is that it has a direct impact on positive grid corrosion. Figure 3 shows the correlation between PPP and a "grid corrosion rate acceleration factor" which is a measure of how fast the grid will corrode relative to an optimal PPP level, which has a factor of 1.0. The corrosion acceleration factors were derived from J. J. Lander's research at the US Naval Research Center during the period between 1951-1956.

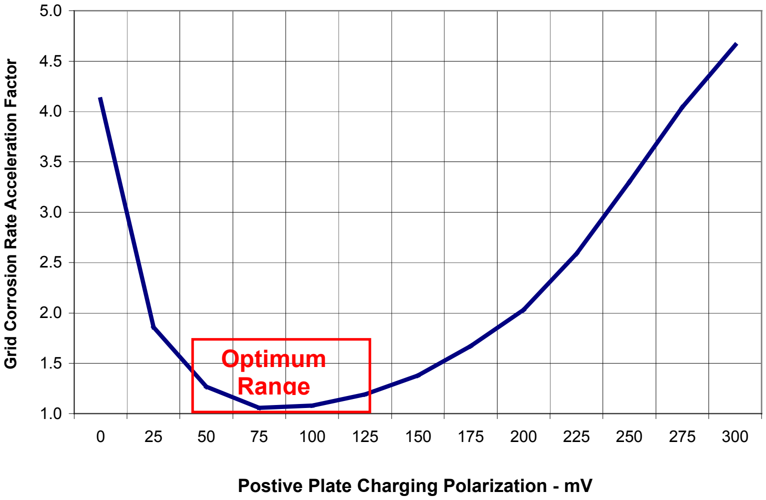

Figure 3: Corrosion rate acceleration factor versus PPP

Figure 3 shows that the higher the PPP, the faster is the positive grid corrosion. There exists an optimal range of PPP where the corrosion acceleration rates are close to unity, namely, 50-120 mV.

The PPP is directly related to the level of equalization/float voltage. The higher the float voltage, the higher the PPP, the faster the corrosion rate. Figure 4 shows the PPP as a function of the equalization/float voltage at various temperatures.

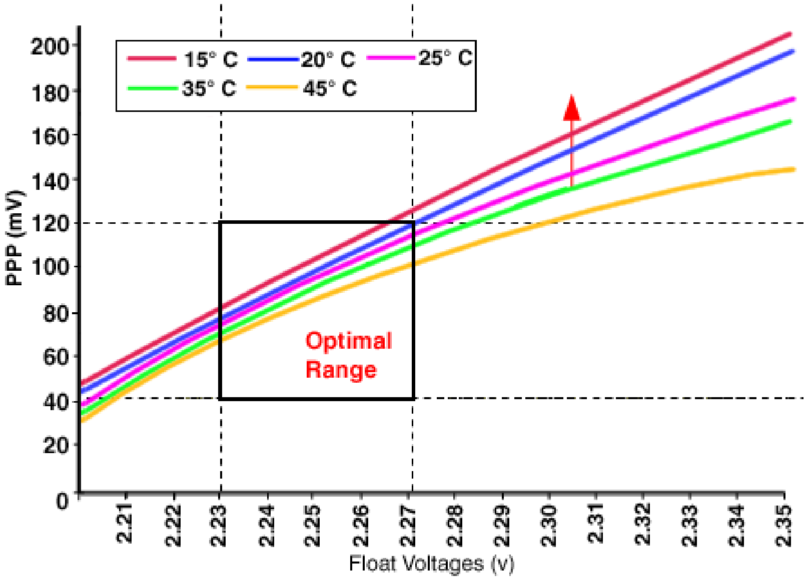

Figure 4: Positive plate polarization (PPP) as a function equalization/float voltage

As shown in Figure 4, maintaining an optimal PPP dictates the application of low equalization/float voltage in the range of 2.23 – 2.27 volts per cell (VPC). The application of elevated per cell voltages during equalization and float charging, typically in the range of 2.3-2.6 VPC, clearly results in higher levels of PPP (in excess of 150 mV) and would thus result in more than doubling the corrosion rate.

The reduction in cell life due to elevated cell voltages during equalization and float charging can be plotted as a function of the applied cell voltage as shown in Figure 4. Elevating cell voltages beyond 2.3 VPC can result in more than 40% reduction in battery life. In practice, equalization is achieved using much higher cell voltages, namely 2.4-2.6 VPC. It can be clearly seen from Figure 5 that the reduction in cell life can exceed 80%. This is a significant penalty that many battery users fail to recognize.

The options to users, until now, have been quite limited. If they choose not to equalize their battery strings, undercharged cells significantly limit the capacity of their strings and reduce battery life. On the other hand, if they choose to equalize their battery strings, overcharged cells may fail and could jeopardize the battery life. Now, a new option is available: individual battery equalization. Before exploring this new concept, it is worthwhile to look at one of the most commonly used devices to prevent gassing of cells during equalization charging, namely shunt regulators.

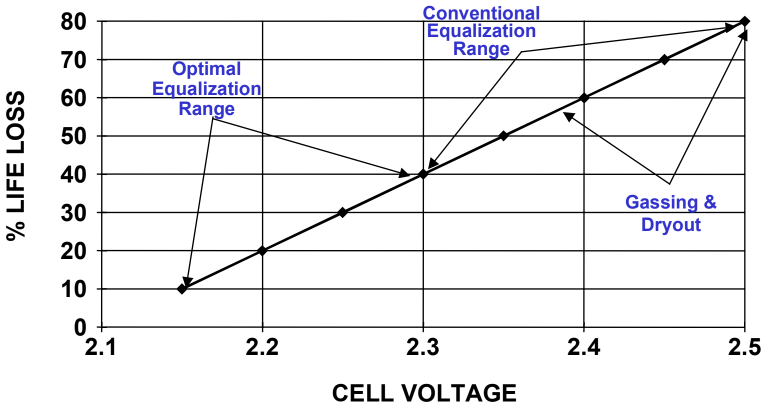

Figure 5: Reduction in cell life at elevated cell voltages

IV. Individual Battery Equalization

In order to prevent the adverse effects of improper charging of battery modules, individual modules need to be maintained at an equalized charge level. The property of individual cell voltages possessing the same value once they have reached the final state of charge can be utilized to achieve this task.

One technique that has been widely used to circumvent the negative impacts of string equalization is individual cell balancing using shunt regulators. Shunt regulator devices are used across each cell to bypass charge current when the battery voltage exceeds a preset level. The basic structure of a shunt regulator consists of a resistive element, a switching device along with some control circuitry. The switching device is controlled to bypass a preset level of current when the cell voltage exceeds a certain limit. The bypassed energy is dissipated as heat within the resistive element. Although this technique is somewhat effective in limiting gassing or overcharging of good cells, it has many drawbacks.

1. The amount of current bypassed is quite limited since all the energy is dissipated as heat in the resistive element. Hence, the bypass current capability is limited to only 100-200mA.
2. Shunt regulators are only effective during overcharge periods. Hence, cells are still subjected to high voltages, thus accelerating grid corrosion rates and reducing battery life. In addition, no balancing is accomplished during discharge and idle modes.

Other active battery equalization schemes have been proposed that utilize more efficient bypass circuitry, which shunts the charging current around overcharged cells to other cells within the string. However, most of these approaches utilize dedicated DC-to-DC converters and/or include multi-winding transformer structures thus making it harder to modularize for different battery strings and bus voltages. The need for a modular, easily configurable and highly efficient battery equalizer is paramount.

A new scheme, which utilizes modular non-dissipative charge equalization modules, has been developed by PowerDesigners. PowerCheq™ is a bidirectional charge equalization device that is connected across pairs of batteries within a string (Fig. 6). A battery string with N batteries requires N-1 PowerCheq™ modules (Fig. 7). The PowerCheq™ modules interconnect batteries in a series string creating a bidirectional charge transfer path between neighboring batteries and enabling the entire battery string to be equalized. Bi-directional equalization ensures that all batteries in a string are equalized no matter where the low voltage battery is located.

Figure 6: The new PowerCheq™ module

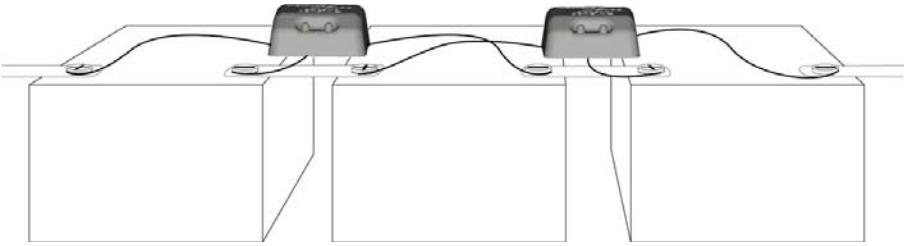

Figure 7: Staggering PowerCheq™ modules across a battery string

V. Experimental Verification

In order to verify the performance of individual battery equalization on battery performance and life, an experimental study was conducted. The tests performed simulated an electric scooter drive cycles using two Yuasa NP24-12B lead-acid battery packs that are commonly used for electric scooters. One of the battery packs was equipped with PowerCheq$^{\text{TM}}$ battery charge equalizers in order to evaluate their effects on cycle life performance. Similar tests were conducted on both battery packs and various performance data were collected and compared. The life cycle tests consisted of the following:

- 2 Conditioning Cycles
- 8 Capacity Tests
- 8 Peak Power Tests
- 152 Simulated Scooter Drive Cycles

Preliminary testing was performed on all batteries in order to determine their initial state of health. During this stage, no equalizers were used on any of the modules, and all nine modules were connected in series as one whole pack.

Initial Conditioning

For initial conditioning of the battery packs, two drive cycles were performed. This was followed by a discharge at a 5-hour rate to a module cutoff voltage of 11.0 V, followed by a full recharge. A second 5-hour rate discharge was performed to a cutoff voltage of 11.5 V during discharge.

Drive Cycles

The simulated drive cycles consisted of the following steps starting with a full battery:

1. Discharge according to the drive simulation protocol.
2. Rest 5 minutes.
3. Charge according to a predefined charge protocol.
4. Rest 10 minutes.
5. Go to step 1 and continue until reaching the stop condition (38.4 V).

Initial capacity based on simulated drive cycles was determined by taking the average energy output of the first five cycles. Adjustments were made to initial capacity due to modifications in charge and discharge algorithms during progress of testing in first stage to match the performance of the two packs.

Capacity Tests

These tests were performed at a 5-hour discharge rate to a module cutoff voltage of 10.5 V followed by a full recharge. The capacity tests were conducted in compliance with the USABC general test procedures.

Peak Power Tests

Peak power tests were performed according to United States Advanced Battery Consortium (USABC) test procedures and battery manufacturer limits. The purpose of peak power tests is to determine the sustained (30 seconds) discharge power capability. This test was performed at ten levels of depths-of-discharge (DOD), from 0% DOD to 90% DOD in 10% intervals during a single discharge. The value calculated at 80% DOD is particularly important because this is the point at which the USABC power goal is defined, and the technology performance at this point is compared with this goal.

Test Setup Description

The Yuasa NP24-12B Sealed Lead Acid battery used in this study has a rated capacity 20.4 Amp-hours (Ah) at a C/5 discharge rate, and its nominal voltage is 12 Volts. The battery modules were configured into two separate series connected packs (Figure 8) with each pack consisting of 4 battery modules and a nominal capacity of 48 Volts.

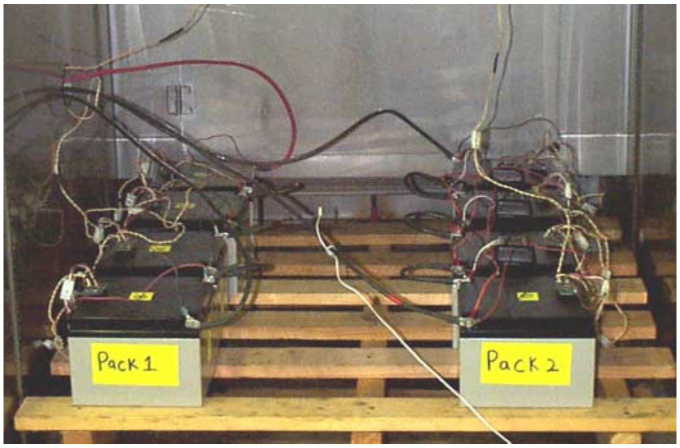

Figure 8. Battery packs setup during simulation testing.

A battery monitoring system was used to log the individual battery voltages and temperatures in both packs during testing. The battery equalization devices were installed on one battery pack as described earlier (Pack 2 in Fig. 8). Both battery packs were placed in an environmental chamber operating with a controlled ambient temperature of 25 ± 1 °C.

The cycling of the battery packs in this study was performed using an AeroVironment ABC-150 Advanced Battery Cycler at Southern California Edison EV test facility. Battery data was sampled and simultaneously recorded and communicated back to a PC via an RS-232 interface.

Test Results

The battery packs were cycled according to the above-described drive cycle. In order to determine the impact of equalization on battery life, end of life was defined as the point at which the energy output of the battery packs dropped to 80% of initial capacity based on drive cycle energy output. The test results clearly show that the response of the battery packs to the drive cycle test routine was significantly different. The capacity of Pack 1 (without the battery equalizers) dropped considerably throughout the last phase of the testing. On the other hand, Pack 2 (with the battery equalizers) had a more consistent capacity throughout the test. Figure 9 shows the simulated scooter drive cycle energy output (in kWh). The spikes on the chart resulted after the battery packs resumed cycling after test interruptions, test algorithm modifications, or reference performance testing. Reference performance testing refers to the set of capacity and peak power tests between simulated drive cycles. The degradation in the performance of Pack 1 (without the equalizers) is quite evident especially in the last 50 cycles. Pack 2 (with the equalizers) performance remained constant throughout drive cycles.

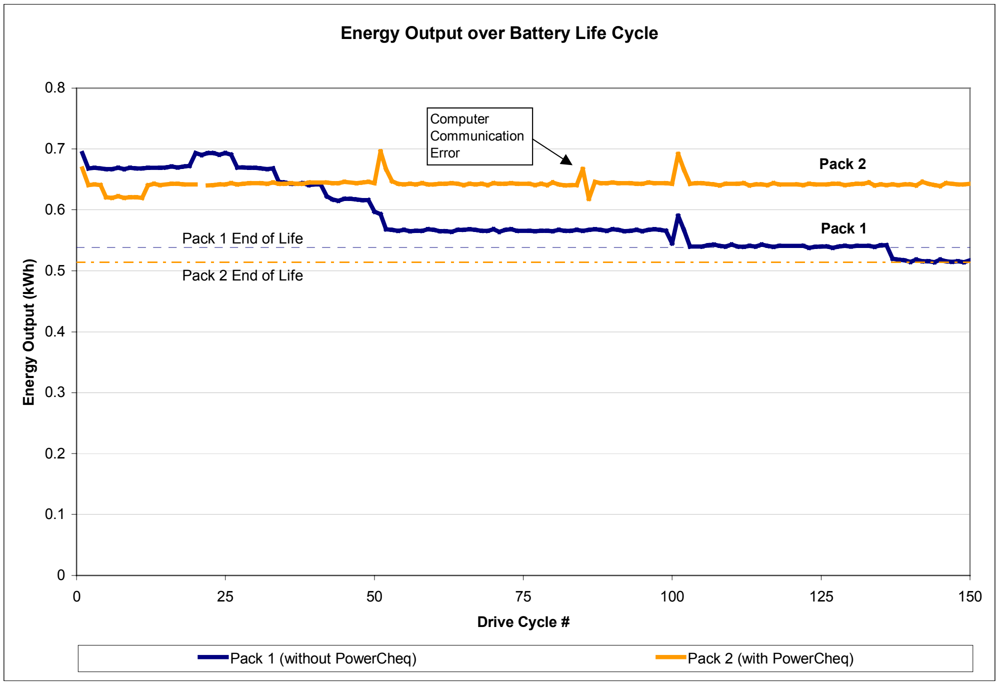

Figure 9: Simulated Scooter Drive Cycles

Figure 10 shows the capacity tests performed on each pack every 50 cycles. As shown in the figure, the capacity of the pack with the equalizers was not affected by cycling for the duration of the test. The decline in the capacity of the battery with no equalizers was caused by one module that became out of balance with the rest of the pack. By comparing capacity test results between the last and first capacity tests, the pack without equalizers lost 35.5% of its capacity while the pack with equalizers gained 2.6% based on Ah output. It is interesting to note that the capacity of the pack with no equalizers dropped considerably with the progress of the test.

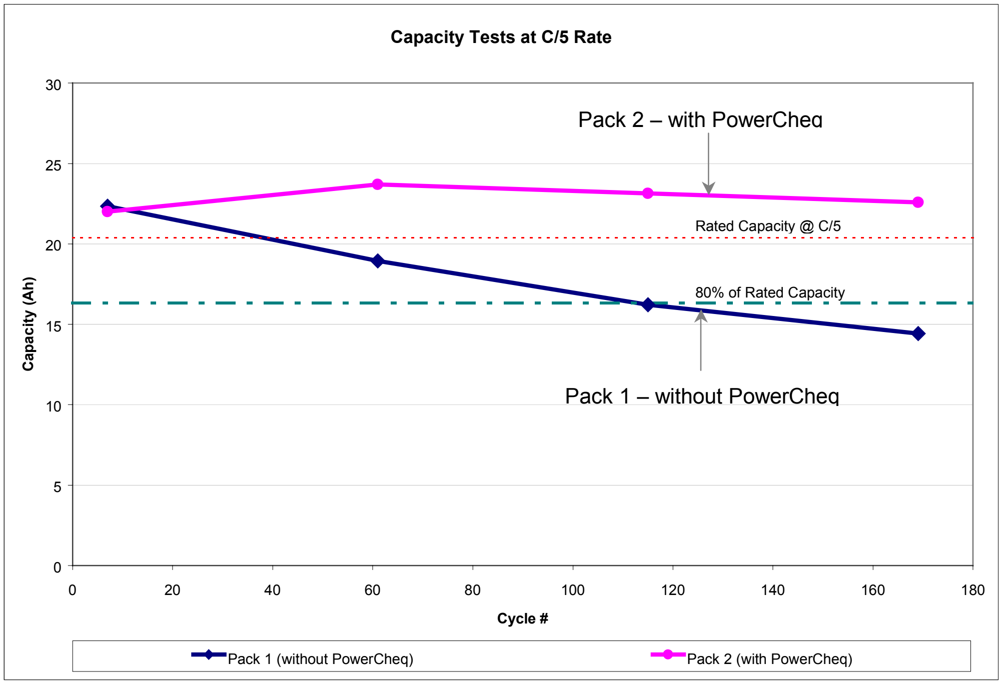

Figure 10: Battery capacity as a function of cycles

Table 1 shows capacity test data for both packs. The overall cycle number refers to the number of cycles including conditioning, capacity tests, peak power tests, and simulated drive cycles. The data clearly shows the degradation in performance of Pack 1 while Pack 2 performance was not affected. In fact, the output power capability of Pack 2 improved after 162 cycles indicating that range of the battery pack will not be affected as the batteries age. The degradation in output power capability of Pack 1 signifies a continuous loss of range due to lack of equalization.

Table 1: Capacity Test Data

Test Cycle #	kWh Out		Ah Out		kWh In		Ah In		% Charge Return	
	Pack 1	Pack 2	Pack 1	Pack 2	Pack 1	Pack 2	Pack 1	Pack 2	Pack 1	Pack 2
6	1.056	1.041	22.11	21.85	1.224	1.222	23.22	23.21	105.0	106.2
7	1.081	1.060	22.57	22.17	1.216	1.222	23.07	23.17	102.2	104.5
60	0.943	1.143	19.30	23.75	1.067	1.384	19.92	25.40	103.2	106.9
61	0.911	1.141	18.59	23.65	1.046	1.353	19.49	25.50	104.8	107.8
114	0.808	1.117	16.42	23.15	0.934	1.320	17.24	24.76	105.0	107.0
115	0.791	1.119	16.00	23.14	0.916	1.323	16.89	24.83	105.6	107.3
168	0.722	1.091	14.59	22.63	0.843	1.302	15.45	24.36	105.9	107.6
169	0.708	1.092	14.25	22.55	0.830	1.296	15.18	24.26	106.5	107.6

Note: Pack 2 was equipped with PowerCheq charge equalizers. Pack 1 failed after 150 cycles (reached 80% of initial capacity)

Figures 11 and 12 show the last capacity tests performed on both packs. As seen from Fig. 10, one of the batteries was out of balance with respect to the rest of the pack resulting in a significant degradation in pack capacity. For the pack equipped with the equalizers, all batteries are in synch and the overall capacity is unaffected.

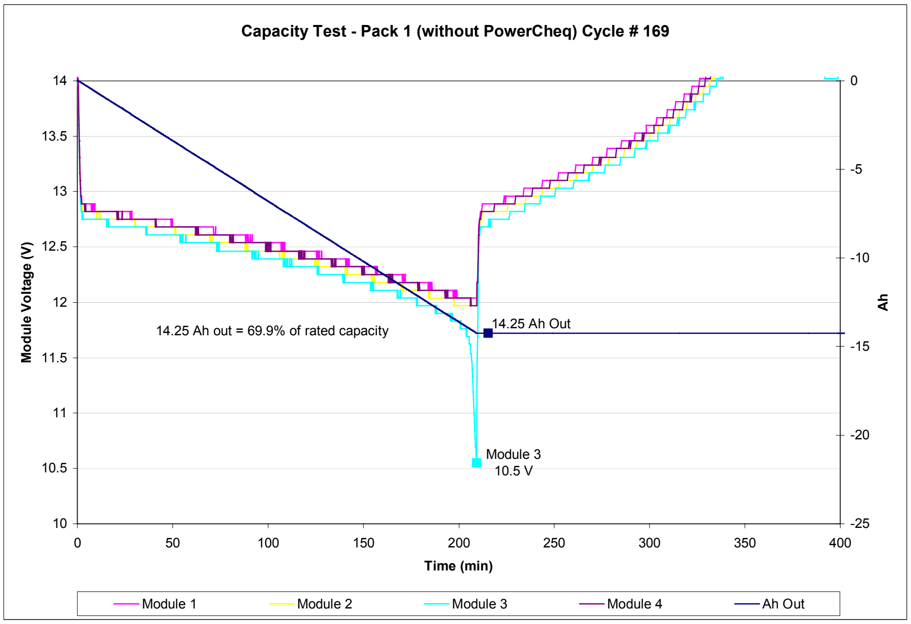

Figure 11: Capacity test after 150 cycles – Pack 1 (without PowerCheq)

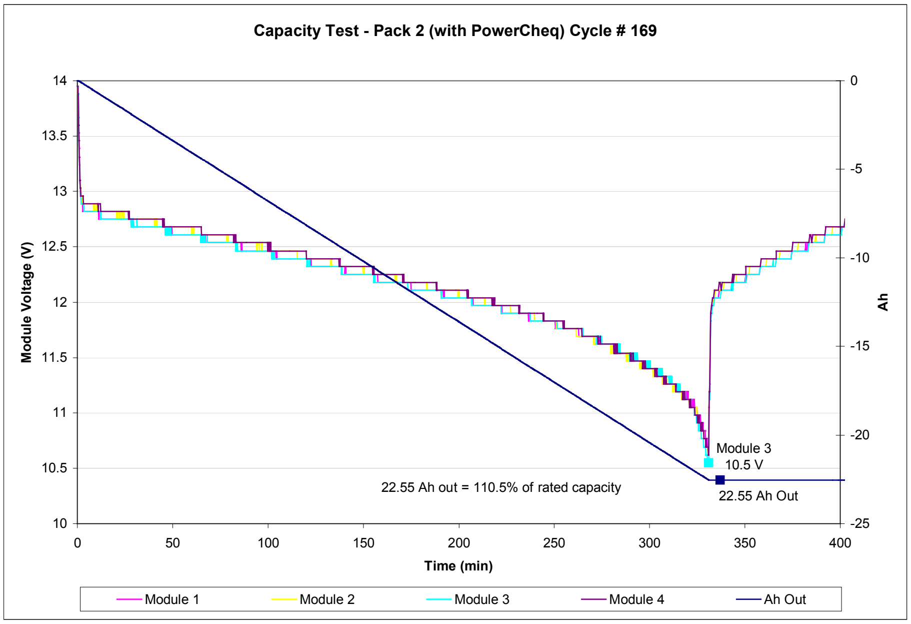

Figure 12: Capacity test after 150 cycles – Pack 2 (with PowerCheq)

A further look at the individual battery voltages for both packs during a charge cycle can shed more light on the performance of the battery equalizers on a cycle by cycle basis. Figures 13 through 16 show the individual battery voltages of both packs during the 130th drive cycle during the charge and discharge phases.

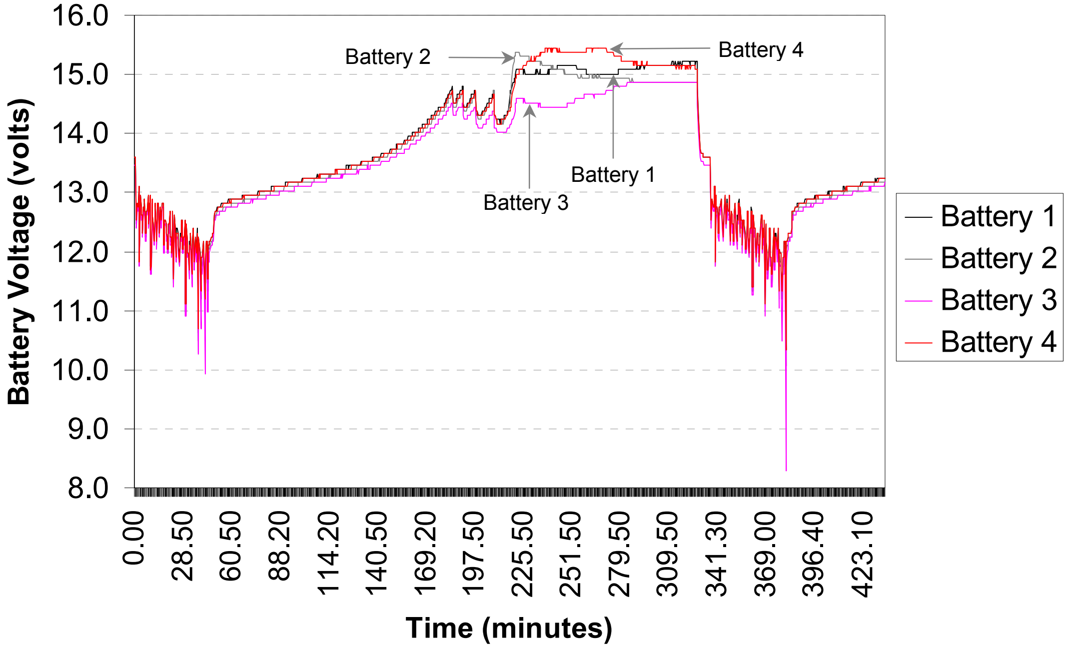

Figure 13: Battery Voltages of Pack 1(without PowerCheq) During 130th Charge & Drive Cycles

For the pack without equalizers (Fig. 13), it can be seen that during the charge phase, battery 3 voltage is noticeably lower than the rest of the pack. In addition, during the equalization phase, batteries 2 and 4 are being over charged (gassed), while battery 3 is still undercharged. This clearly shows how string equalization is inefficient in maintaining batteries within the string at the same charge level. A further look at Fig. 14 shows how battery 3 (the weak module) voltage dropped below 10.5 V during the drive cycle.

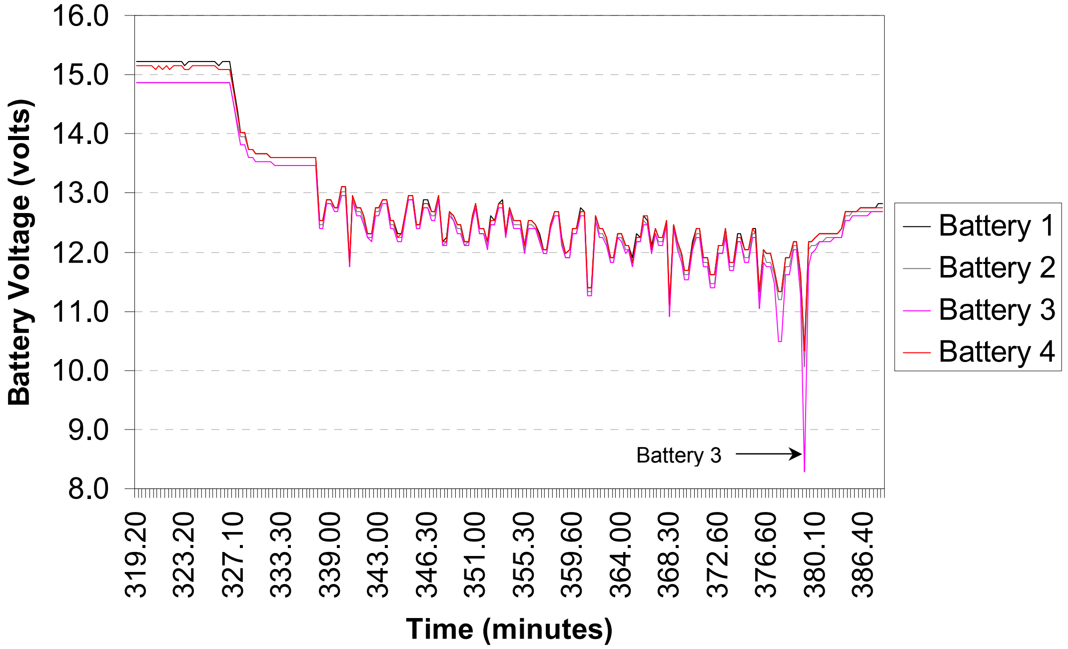

Figure 14: Battery Voltages of Pack 1(without PowerCheq) During the 130th Drive Cycle

For the pack with equalizers (Fig. 15), it can be clearly seen that imbalances between the batteries are eliminated during both the charge and drive cycles. In addition, during the equalization phase, all battery voltages are well regulated at the 15V level (2.5 VPC) signifying that all batteries are properly charged with none being over or under charged. Even during the drive cycle, all batteries are still equalized (Fig. 16). This is due to the fact that the battery equalizers operate not only during the charge phase, but also during discharge and idle phases of operation.

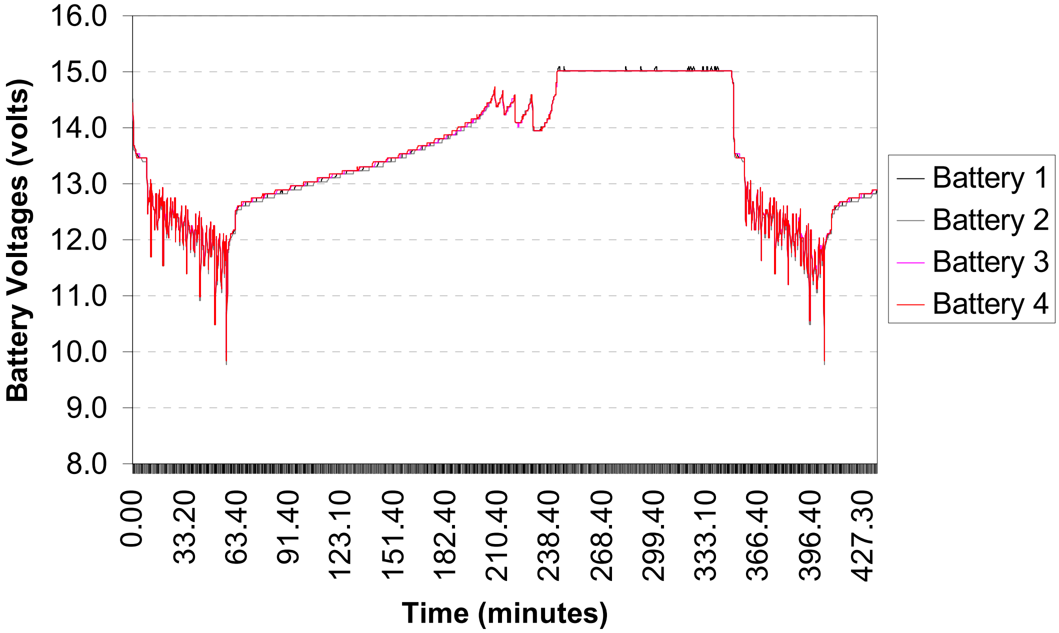

Figure 15: Battery Voltages of Pack 1(with PowerCheq) During the 130th Charge & Drive Cycles

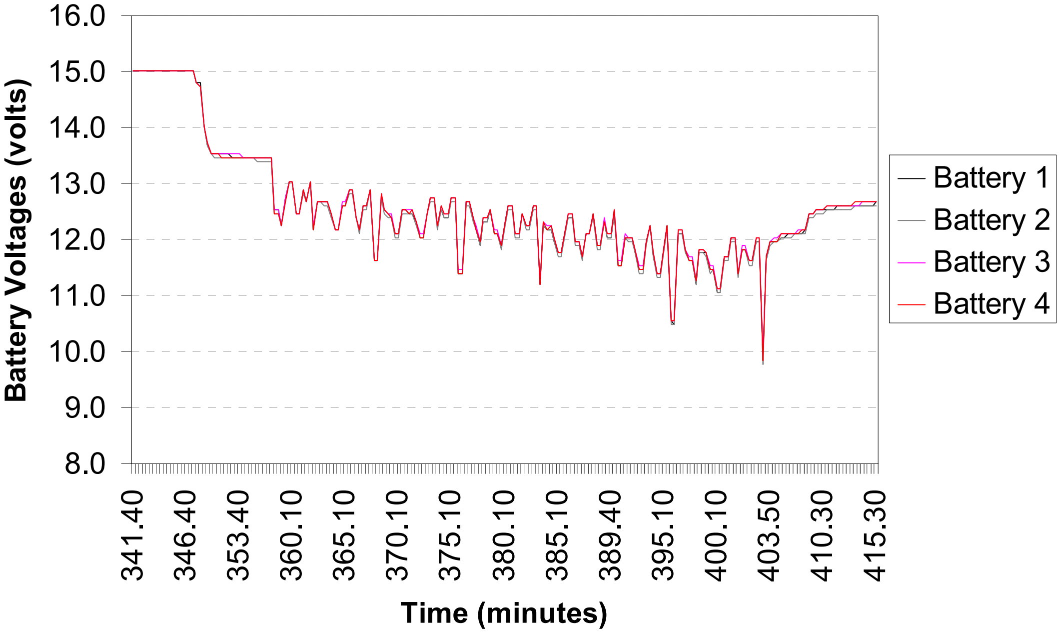

Figure 16: Battery Voltages of Pack 1 (with PowerCheq) During the 130th Drive Cycle

The test was repeated using new sets of batteries and very similar results were obtained. Pack 1 (without equalizers) also failed after approximately 140 drive cycles in both tests. This clearly proves that the lack of equalization will greatly diminish battery life as well as driving range. String equalization, although used during the charge phase, is inefficient in ensuring equalization of the whole pack. Pack 2 (with equalizers) showed no degradation in performance after 150 drive cycles. In fact, the overall string capacity increased slightly after 150 drive cycles. The output power capability of Pack 2 was not affected signifying no reduction in range throughout battery life.

In order to estimate the life improvement due to equalization, testing of Pack 2 was continued and capacity tests were performed every 50 cycles. Pack 2 went through 465 cycles, 425 of those are simulated drive cycles before its capacity dropped to 80% of the initial value (as calculated for the first five cycles). This represents more than 300% improvement in battery life. In addition, the driving range (output power per cycle) is quite higher and extends further compared to the pack without PowerCheq. Figure 17 shows the energy output throughout the drive cycle testing.

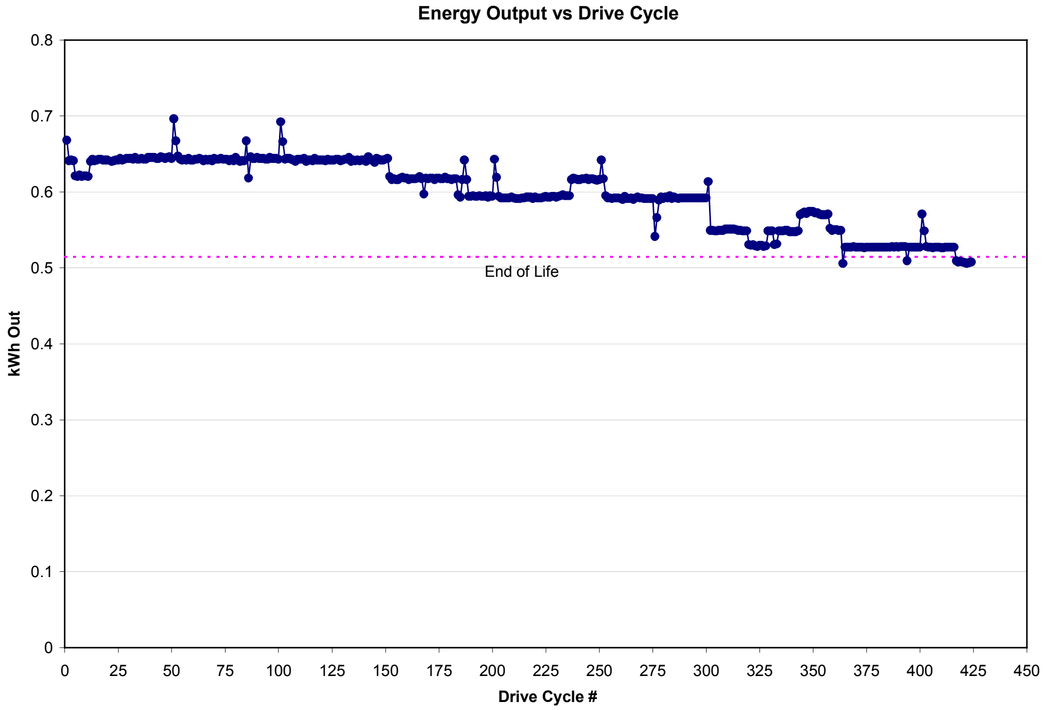

Figure 17. Simulated scooter drive cycles for Pack 2 (with equalizers)

Table 2 below illustrates a comparison between drive cycles 150, 385, and 425. Note here that testing of Pack 1 was suspended (the pack without PowerCheq) since its capacity dropped below 80% of its initial capacity after 150 drive cycles. The battery capacity was maintained above 90% through approximately 400 cycles. Table 3 shows the capacity test results for Pack 2.

Figure 18 shows the capacity test results for Pack 2. It can be clearly seen that the capacity of Pack 2 remained higher than 80% throughout 450 drive cycles compared with 140 cycles for Pack 1. It is interesting to note that the manufacturer specifications call for a total 250 cycles with 100% depth of discharge (DOD). Apparently, this tests shows that the capacity of the string is already higher than what the specs call for. This would directly transfer into significant savings to end-users, as batteries equipped with equalizers would outlive their prescribed life span.

Table 2: Drive cycle result comparison for Pack 2 (with equalizers)

	Drive Cycle 150	Drive Cycle 385	Drive Cycle 425
Ah Out	13.68	11.54	10.59
kWh Out	0.643	0.552	0.507
Ah In	15.08	13.09	12.02
kWh In	0.819	0.713	0.656
% of Initial Capacity	100.06%	91.97%	80%
Charge Return	110.23%	113.40%	113.47%

Table 3: Capacity test results for Pack 2 (with equalizers)

Cycle #	Ah Out	kWh Out	Ah In	kWh In	% Charge Return
6	21.85	1.041	23.21	1.222	106.2%
60	23.75	1.143	25.40	1.384	106.9%
115	23.14	1.119	24.83	1.323	107.3%
169	22.55	1.092	24.26	1.296	107.6%
222	22.06	1.065	23.89	1.282	108.3%
277	21.09	1.026	23.19	1.248	110.0%
334	20.89	1.016	22.97	1.236	109.96%
385	18.13	0.874	19.746	1.063	108.91%
438	16.83	0.827	19.84	1.084	117.9%
439	16.39	0.809	19.26	1.054	117.5%

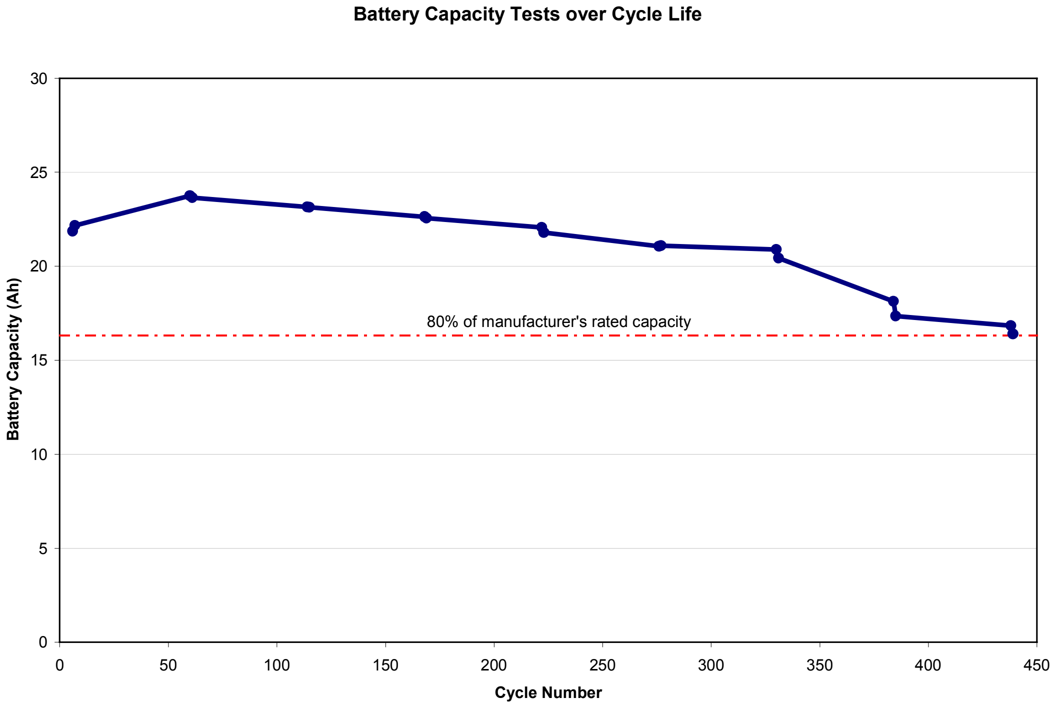

Figure 18: Battery capacity test results for Pack 2 (with equalizers)

VI. Conclusion

Conventional string equalization has been shown to be ineffective in equalizing battery strings as it leads to gassing of good cells and increases the positive plate corrosion rate due to the high positive plate polarization (PPP) thus reducing battery life and performance. Although shunt regulators have been widely used to alleviate the negative impacts of overcharging and gassing, they are also ineffective as they still subject cells to high voltage levels and may mask high resistance cells.

Individual Battery Equalization is the only effective means of achieving true equalization. The main advantages of utilizing individual battery equalizers include:

- Maintaining cells/modules at the same charge level
- Eliminating the need for equalization charging and thus reducing cell voltages during charging
- Reducing the positive plate polarization (PPP) and thus reducing positive grid corrosion
- Improving battery capacity and life while reducing operating costs

The impact of individual battery equalization on the life and performance of lead acid batteries has been studied and quantified. Life cycle tests were performed two similar battery packs where one was equipped with PowerCheqs, a new line of individual battery equalizers from PowerDesigners. The new equalizers offer a real-time equalization function that maintains batteries balanced during charge, discharge, and while sitting idle. The tests clearly reveal that individual battery equalization can significantly improve battery life and performance through extended operational life and increased battery capacity.

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