BATTERY CHARGING IN PHOTOVOLTAIC APPLICATIONS

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ABSTRACT

Throughout the world, battery selection for small photovoltaic (PV) systems is frequently driven by the availability of batteries in the host country. Offshore projects frequently have very limited sources for deep cycling lead-acid batteries and sometimes must employ starting-lighting-ignition (SLI) batteries which are designed especially for power, as opposed to energy, use. SLI batteries are not intended for deep cycling operation, nonetheless, they are commonly found in small PV systems. To compound the problem, battery management is frequently inadequate and the battery subsequently yields very poor performance in these systems. Recent testing of SLI batteries has been implemented at Sandia National Laboratories to assist photovoltaic system integrators in developing a battery management scheme which will help improve SLI battery performance in shallow cycling applications. This paper discusses the test procedure and reports on the successful results obtained from life testing of a 100 Ah flooded SLI lead-acid battery in a simulated PV environment. Mitigation of failure mechanisms which contribute to the early failure of SLI batteries used in stationary environments is also discussed.

INTRODUCTION

A small photovoltaic (PV) system project for domestic power was initiated in Indonesia by an American company to bring electrical power to homes in small remote villages that had no chance of being connected to the power grid in the foreseeable future. The project specified the use of locally manufactured batteries for energy storage. Unfortunately, deep cycling batteries were economically unfeasible and the use of SLI batteries suggested that the battery would have very short life, on the order of 6 to 18 months, given previous experience with the use of SLI batteries in similar operations. Using a cost benefit analysis approach, the system integrator determined that by considering the initial cost of an off-the-shelf SLI battery, the analysis indicated that a reasonable return on investment could be realized if the SLI battery functioned satisfactorily for at least three years. The American company approached Sandia National Laboratories (SNL) and requested help in evaluating the selected foreign battery for appropriateness in the domestic power application. They also asked for design assistance help in developing an effective battery management strategy. An agreement was reached in late summer of 1996 and the project got underway.

TEST SPECIFICATIONS

To initiate the testing program, three each different size automotive starting-lighting-ignition (SLI), dry-charged, 12 volt batteries, 40 Ah, 65 Ah, and 100 Ah, were received in October 1996, at SNL for testing for potential use as a PV battery for an up to 200 Wh daily load application. The application for which the batteries were to be tested was defined to be limited to small DC lighting and radio/TV loads. It was also specified that the control system would be programmed to keep the battery from falling below 11.8 volts, the low voltage disconnect (LVD) point, which was defined to be the equivalent of about 60% depth of discharge (DOD), the maximum desired DOD. In general, SLI batteries have a life expectancy in this type of application of 6 months to 1 year. The major purpose of the test was to determine if careful management of the battery could extend expected life to at least three years. The system integrator desired a minimum of 1000 daily operational cycles (three year operational life) for the battery and was committed to developing a system controller and battery charger that would manage the system within the tight constraints necessary to meet the battery life specification. The results of the test would indicate if an SLI battery could meet the three year life specification and would help in determining an optimum battery management strategy and also indicate a minimum battery maintenance program to keep the battery as healthy as possible.

THE TEST PLAN

A test plan was developed to not just cycle the battery but to also stress the battery in a similar way that typical PV systems stress batteries while still maintaining an operating regime that would support the load requirements and not be excessively abusive to the battery. Because of the real expectations of PV power not being reliably available each and every day, it was determined that the battery would be exposed to a deficit cycling regime during routine operations. Consequently, a decision was made to mildly stress the battery through deficit cycling to more closely match the stress to be realized in a real environment. One daily operational load cycle would result in the removal of 10% of the measured capacity of the battery during the discharge period, and during the charge period, 9% would be returned resulting in a daily decrease in the state of charge of the battery. The battery would cycle in this manner until it reached about 60% of measured capacity, the LVD point. Then the battery would be recharged to 125% of measured capacity, as recommended by the battery manufacturer, and the operational cycling would resume. End of life for the battery was defined as the point when the battery could no longer support the daily operational cycling requirement, or when 1000 operational cycles were completed.

INITIATING THE TESTING PROGRAM

Following the development of the Test Plan and definition of the operational cycling regime, the battery manufacturer's specification sheet was closely reviewed to determine the procedures to follow in preparing the dry-charged SLI battery for service. The battery was very carefully prepped following the manufacturer's instructions from their specification sheet which described initial charge procedures, voltage settings, and current and temperature limits for normal battery preparation for SLI service. Although deep discharge is not a recommended procedure for SLI battery testing, following the completion of the preparation process, the battery was capacity tested to 1.75 volts per cell (vpc) to provide baseline capacity data for the battery. The capacity test for the 100 Ah battery, which was conducted at the 8 hour rate, resulted in the battery producing 88 Ah for initial capacity. The battery was immediately recharged to 125% of the discharged ampere hours and daily operational cycling was initiated.

The three batteries operated for several months in the cycling regime before the two smaller batteries began to show early signs of failure by not being able to support the 10% load requirement in one cycle. The two smaller batteries were taken off test with the determination that the batteries were too small to effectively support the load requirements as specified. The 100 Ah battery continued to perform daily shallow cycling with no apparent signs of degradation.

INITIAL FINDINGS

Inspection of Figure 1 shows the consistency of the cycling for a typical deficit charge period in which the battery was not fully recharged following each operational discharge. It indicates that 12 to 13 operational cycles are completed before the battery is discharged to the LVD voltage of 11.8 volts, the maximum discharge point of 60% SOC for the battery. In other words, the battery would be operated for approximately 2 weeks of daily operations at an intermediate SOC before it reached LVD. Figure 2 was the cycling activity at the end of the test where only 5 cycles were completed prior to reaching LVD. More discussion on Figure 2 follows later.

Figure 3 shows the typical periodic cycling of the battery. Each box symbol indicates the end-of-charge voltage reached while returning 9% of charge removed for operational cycles and the 125% full charges for more than 1,000 operational cycles. One of the most important observations to be noted is the consistency of the battery response throughout the test period shown. Note also that there are several excursions outside of the nominal data points. These excursions are attributed to data acquisition errors. Prior to the point where the arrow is pointing, is may be noted that the end of charge voltage for each 125% recharge action is falling rapidly indicating that the battery is not being fully recharged. An investigation yielded information that significant stratification was occurring. This observation will be discussed further later in the paper. From the point of the arrow, stratification mitigation action was conducted which stabilized the EOC voltages very quickly. It may also be noted that there is a reasonably low rate linear trend in the reduction of the EOC voltages after each 125% recharge point beyond the 3500 Hour point. This trend is typical of the way an SLI battery naturally ages in shallow cycling operations.

FINAL FINDINGS

An interesting and important observation was made at the test point noted by the arrow as the stratification mitigation point in Figure 3. Stationary batteries that are cycled are routinely equalized in normal operations. Equalization of stationary batteries in a cycling environment is necessary to both bring the cells to nearly equal states of charge and to agitate the electrolyte through top-of-charge bubbling action which helps to "stir" the heavy electrolyte in the bottom of the battery with the light electrolyte in the top of the battery. Typically, PV systems are designed such that routine equalization of batteries is not possible. Throughout the test period, an equalization charge was never performed for the battery. The decision not to perform equalization charges is based on the typical energy limitations of small photovoltaic systems. Because of industrial practice, the tendency is to minimize the number of PV panels in a system, defined primarily by the system load and not battery requirements, creates the situation where PV systems cannot consistently provide an effective equalization charge. Without the equalization cycle, stratification was imminent.

Figure 4 shows the variation, and obvious acid stratification, of the specific gravity of the battery in the early stages of the test program. Because only minimal active gassing was experienced at near top-of-charge, even near the end of the 125% overcharge, there was little agitation and stirring of the electrolyte for the battery. It was also noted that during routine charge/discharge operations, relatively large bubbles formed between the plates and the separators that tended also to reduce capacity. It was feared that severe acid stratification may be taking place because of the lack of agitation. Specific gravity data in Figures 4, 5, and 6 illustrate the stratification effects by showing the specific gravity at the top, in the center and near the bottom of the battery for each cell. Indeed, acid stratification is present at these various states of charge. It was speculated that the effect of stratification was responsible for the decline of the end-of-charge voltage following each 125% charge cycle prior to the point indicated in Figure 3 at the arrow. This speculation was verified by the application of a destratification process at about the 550 hour point following which, the end-of-charge voltage began a slight rise and then leveled off until about the 3500 hour point, where it began a slow decline typical of the natural aging process of a battery. Figure 7 shows the specific gravity for all cells following the stratification mitigation procedure. It is interesting to note that stratification of SLI batteries in normal automotive operations is unusual because batteries in vehicles are exposed to the bouncing and maneuvering during normal driving which tends to "stir" the battery electrolyte.

Another important finding, as previously commented on, is associated with the development of large bubbles between the plates that tended to cling to the face of the plates and not routinely release. This was discovered at about the 550 hour point when one side of the battery was dropped approximately ½ inch to observe the level of the electrolyte in the battery. The agitation caused the battery to suddenly release a mass of trapped bubbles which vigorously stirred the electrolyte. This discovery ultimately led to the investigation of the stratification issue. In addition as a result of this discovery, the battery was routinely "dropped" periodically to release the built up bubbles from between the plates. A program was also started to actively de-stratify the battery on a routine schedule. It may also be speculated that periodic equalization charges may have had a positive effect on battery life; however, testing for that finding was beyond the scope of the program as defined.

CONCLUSIONS

The test continued without major interruption for approximately 15 months for a total of 1,020 operational cycles, when it was terminated for convenience as the battery was still able to meet the daily discharge requirements of 10% of initial capacity. A capacity test at the end of the test program indicated that the battery was at 58% of initial capacity, well below the "standard" figure of less than 80% of initial capacity constituting failure. Nonetheless, the battery was still meeting operational specifications; consequently, it was not deemed to be "in failure". Figure 2 shows the daily cycling for the battery just before test termination indicating that the daily load requirements were being met.

Effective life of an SLI battery in a PV system can be more than 3 years if the battery is properly maintained. The primary finding of the test program was that SLI batteries can be a cost effective option for PV systems if proper battery management is correctly applied and timely maintenance is performed. Acid stratification may be the primary failure mechanism for stationary batteries in which the electrolyte is not periodically agitated sufficiently to de-stratify the battery. Proper battery system management is essential in order to realize maximum life from SLI batteries used in PV systems.

FIGURES

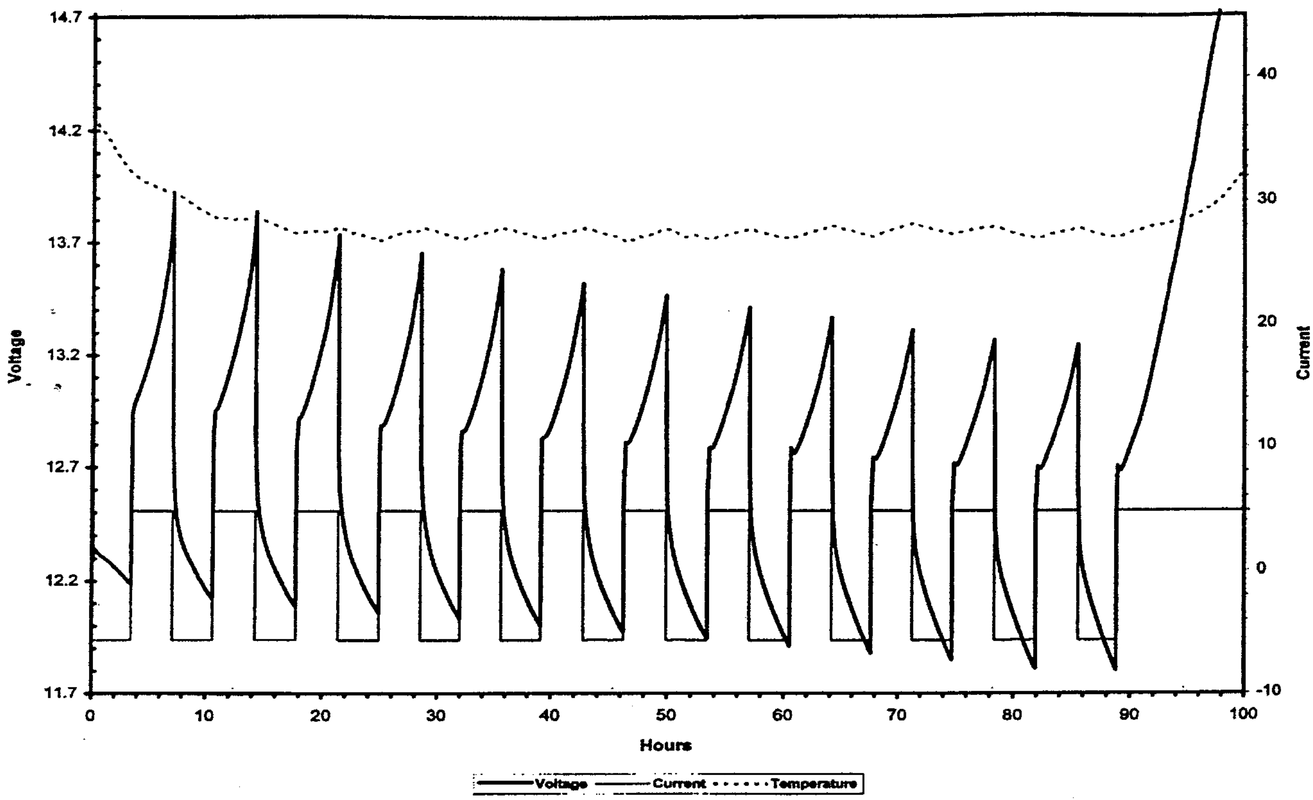


Figure 1. Initial daily cycling showing the drop in SOC as the battery is exposed to daily deficit charging.

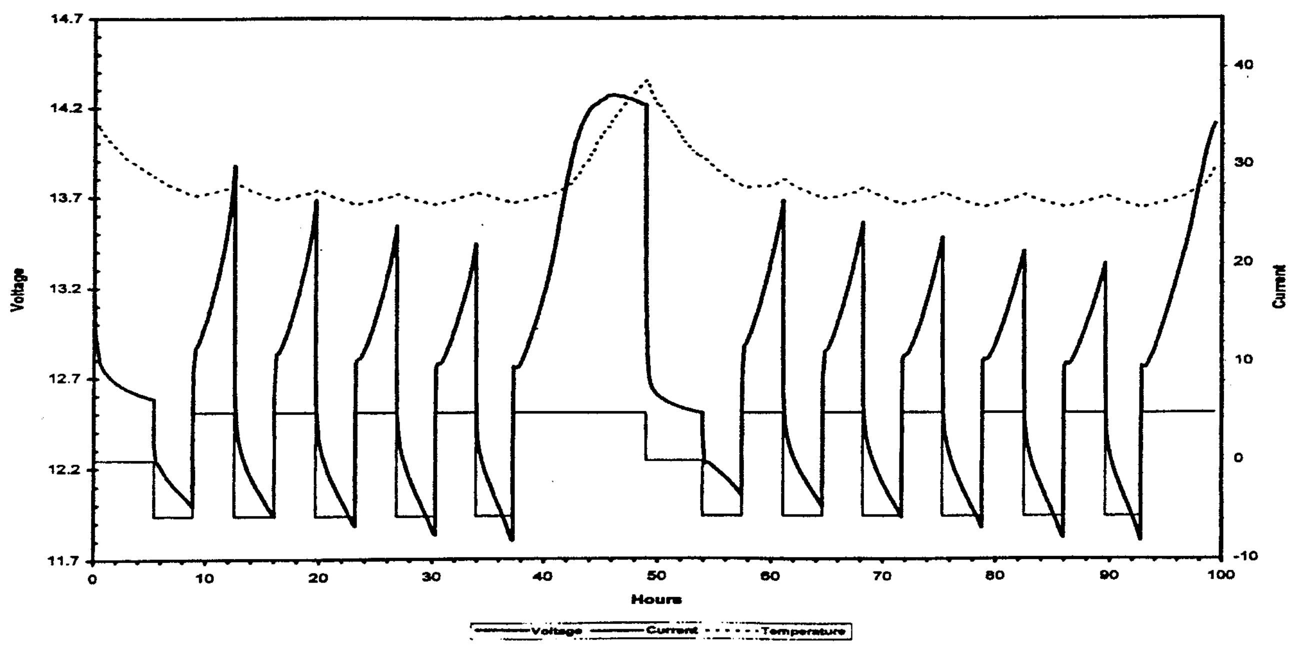


Figure 2. End of test daily cycling showing 5 cycles can be realized before LVD is reached.

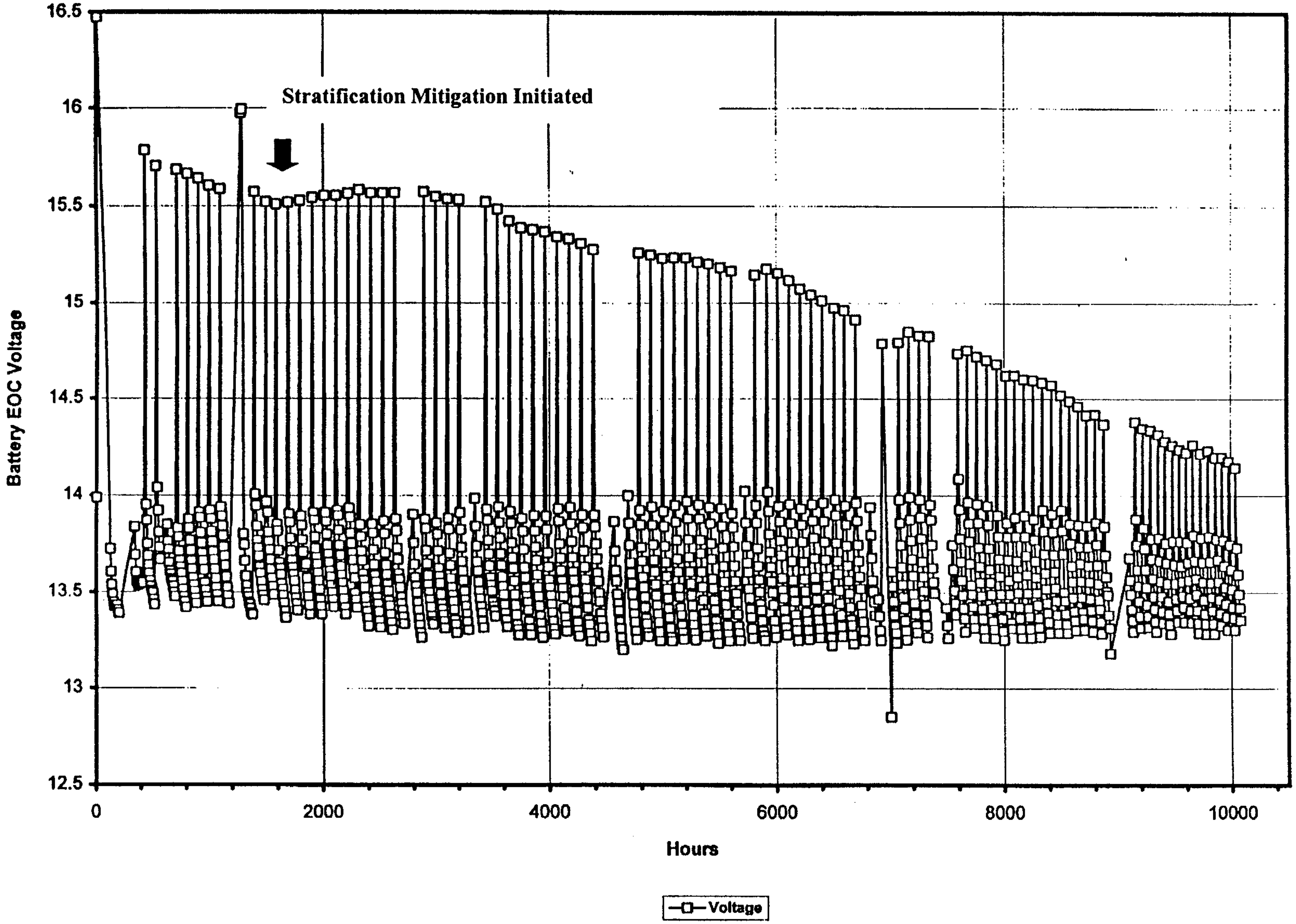
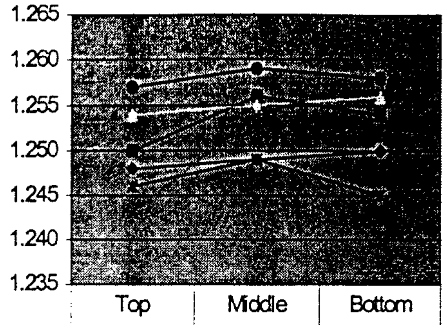
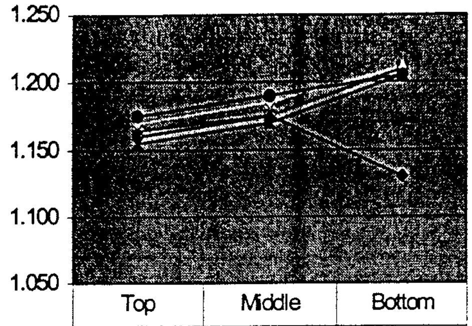


Figure 3. End of Charge (EOC) voltages for daily and full recharge charging activities.



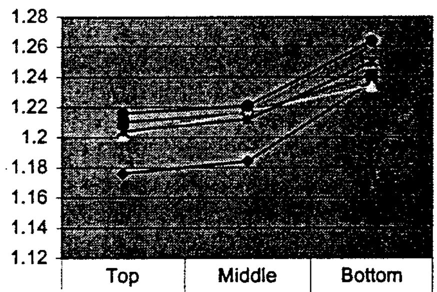
	Top	Middle	Bottom
Cell #1	1.248	1.249	1.250
Cell #2	1.250	1.256	1.254
Cell #3	1.254	1.255	1.256
Cell #4	1.243	1.254	1.258
Cell #5	1.246	1.249	1.245
Cell #6	1.257	1.259	1.258

Figure 4. Specific Gravity for all Cells at 91% SOC early in test program.



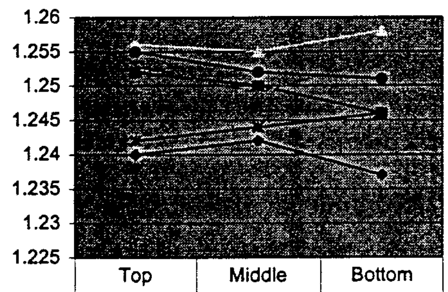
	Top	Middle	Bottom
Cell #1	1.160	1.175	1.130
Cell #2	1.165	1.175	1.210
Cell #3	1.170	1.185	1.211
Cell #4	1.165	1.180	1.225
Cell #5	1.155	1.170	1.205
Cell #6	1.175	1.190	1.205

Figure 5. Specific Gravity for all Cells at 100% SOC showing substantial stratification even after full charge applied.



	Top	Middle	Bottom
Cell #1	1.176	1.184	1.237
Cell #2	1.21	1.216	1.241
Cell #3	1.201	1.217	1.234
Cell #4	1.204	1.217	1.261
Cell #5	1.204	1.212	1.25
Cell #6	1.216	1.221	1.264

Figure 6. Initial Spread in Specific Gravity at 60% SOC indicating level of stratification.



	Top	Middle	Bottom
Cell #1	1.24	1.242	1.237
Cell #2	1.252	1.25	1.246
Cell #3	1.256	1.255	1.258
Cell #4	1.253	1.249	1.254
Cell #5	1.242	1.244	1.246
Cell #6	1.255	1.252	1.251

Figure 7. Specific Gravity at 100% SOC following de-stratification operation.