Final Long-Term Duty Cycle 60-Day Report

Regulation Energy Management (REM) Duty Cycle
Battery Module: A123 #5, Channel 1

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PREPARED FOR

National Renewable Energy Laboratory

PREPARED BY

Center for Sustainable Energy

Center for Sustainable Energy™

9325 Sky Park Court, Suite 100
San Diego, CA 92123
858.244.1177 *phone*
www.energycenter.org

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I. Summary of Operations

This test report provides a summary of the complete long-term regulation energy management (REM) duty cycling testing performed on the A123 Battery Module #5. Prior to the REM testing discussed herein, this module was subjected to automotive cycling and over a year of additional stationary storage cycling and degraded to a state at which it retained only 80% of its nameplate capacity and displayed approximately150% of its beginning of life impedance. Subsequent long-term REM testing included over 200 non-consecutive days of REM cycling. Between each approximately 60-day period, there was a Reference Performance Test (RPT) conducted on the battery module under test. The Reference Performance Tests served as an indication of battery degradation under long-term REM cycling. Table 1 summarizes the testing time of each REM cycling period under this long-term protocol.

Table 1: Overview of REM Cycling Periods

Period	Time Range	Elapsed Calendar Time[1]	Cycling Days
Period 1	Oct. 2013-Jan. 2014	94.5	59.8
Period 2	Jan. 2014-June 2014	168.1	81.3
Period 3	June 2014-Oct. 2014	123.0	61.6
Total		385.6	202.7

[1] Elapsed calendar time includes the time for completion of the pre and post Reference Performance Tests.

II. Results of Reference Performance Tests (RPTs)

The Reference Performance Tests consisted of capacity and DC impedance (or resistance) measurements. Summary results of the RPTs conducted before, after, and during long-term REM duty cycle testing are presented below. All the RPT occurrences during this long-term test protocol were performed locally via the Battery Control Software. Table 2 summarizes the results of the capacity tests performed on the A123 Module #5 during long-term REM cycling.

Table 2: Summary of Capacity Tests

	Oct. 2013*	Jan. 2014*	June 2014	Oct. 2014
Direct Capacity (Ah)[2]	37.2	22.4	43.4	42.8
Direct Capacity as % of Nameplate	65.3	39.2	76.1	75.1
Inferred Capacity (Ah)[3]	40.9	25.7	43.1	41.8
Inferred Capacity as % of Nameplate	71.7	45.1	75.5	73.4
Direct Energy (kWh)[4]	2.8	1.7	3.2	3.2
Direct Energy Efficiency (%)	97.8	94.8	96.7	96.3
Inferred Energy (kWh)[5]	3.1	2.0	3.3	3.2
	Period 1	**Period 2**	**Period 3**	
REM Discharge Throughput	403,926.1	573,822.8	334,953.2	

[2] The Direct Capacity (Ah) is the direct discharge capacity measured during the C/5 capacity test.

[3] The Inferred Capacity (Ah) is calculated by scaling the Direct Capacity (Ah) with the range of battery capacity cycled as estimated from open-circuit (i.e. unloaded) cell voltages before and after recharge during the C/5 capacity test. Minimum cell voltages in particular were used which provides a conservative capacity measurement.

[4] The Direct Energy (kWh) is the direct discharge energy measured during the C/5 capacity test.

[5] The Inferred Energy (kWh) is calculated by scaling the Direct Energy (kWh) with the range of battery capacity cycled as estimated from open-circuit (i.e. unloaded) cell voltages before and after recharge during the C/5 capacity test.

(kWh)[6]			
Percent Capacity Change per GWh of REM Discharge Throughput (%/GWh)[7]	0.66	-0.53	0.06
*Note: The cells of the battery module were not balanced before each of the tests in the Reference Performance Test.			

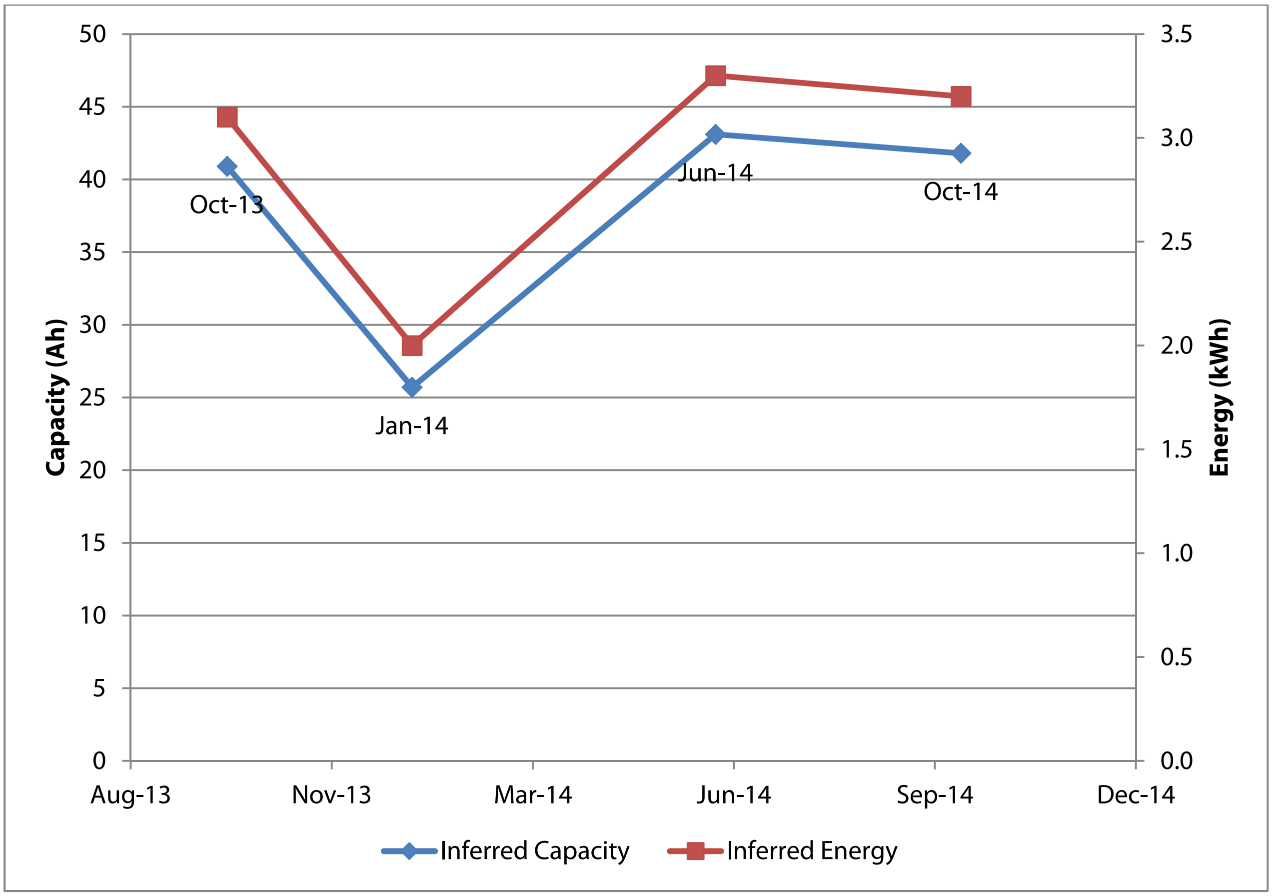

Figure 1: Capacity Degradation of Battery over REM Cycling

[6] The REM Throughput (kWh) is the sum of the kWh In and the absolute value of the kWh Out during REM cycling days.

[7] The Percent Capacity Change per GWh REM Discharge Throughput (%/GWh) is ratio of capacity loss as a percentage of nameplate capacity (57 Ah) to the GWh of discharge out of the battery during the REM cycling. It is important to note that each cycling period did not have the same amount of GWh discharge throughput.

Before each capacity test, the testing protocol called for the battery cells to be fully charged and balanced to 100% SOC. However, a setting had been disabled in the Battery Control Software that prohibited the cells from balancing during some of the capacity tests. When cells were not balanced, the battery was charged until the highest voltage cell reached its high voltage limit, and discharged until the lowest voltage cell reached its low voltage limit.[8] Thus, at the end of charge, many cells were at less than 100% SOC, and at the end of discharge many cells were at greater than 0% SOC, which greatly limited the available capacity. .As soon as it was discovered in late March 2014 that the cell balancing setting had been disabled, though, it was re-enabled and balancing of the cells before each test of the RPT was resumed.

Testing of the pack before cell balancing was re-activated shows that performance degraded quickly due to REM testing. The RPTs in October 2013 and January 2014 show that 26.1% of nameplate capacity was lost over this period. However, comparing the RPT results before (January 2014) and after (June 2014) cell balancing was re-enabled reveals that this adjustment nearly doubled the available capacity. This implies that the large decrease in performance between October 2013 and January 2014 was due to growing cell imbalance, and thusly that REM cycling can exacerbate cell imbalance within a pack. The capacity recover in June 2014, on the other hand, illustrates the ability of cell balancing circuity to greatly improve pack performance.

Table 3 below summarizes the average DC impedance of the A123 Module #5 cells for the charge and discharge pulses of each Pulse Characterization Test (PCT). In the table it appears as though the impedance of the cells decreases between the January 2014 and October 2014 PCTs. However, if we look at the average cell temperatures of the module during each of the PCTs, we will see that between January 2014 and October 2014, the average cell temperatures of the module increases. This trend is shown in Figure 2. The greater the cell temperatures at the time of performing a PCT, the lower the impedance of the cells will be. Therefore, had we wanted to more accurately compare DC impedance degradation over time during REM cycling, we would have needed to control for cell temperatures when performing each PCT. Unfortunately this control capability was not available at the employed test facility.

Comparison of the October 2013 and June 2014 test data, where the cell temperatures were similar, however, implies that the resistance of the module has not been significantly impacted by REM cycling.

[8] Because capacity and pulse characterization tests were conducted via the Battery Control Software, charge and discharge time to reach the maximum and minimum cell voltage limits was estimated. Therefore, the maximum or minimum cell voltage reached at the end of the charge and discharge may be slightly different than the maximum and minimum cell voltage limits. The difference, though, is insignificant – less than 1.5%.

Table 3: Average DC Impedance and Average Temperatures of Module Cells during REM Cycling

Pulses	Oct. 2013	Jan. 2014	June 2014	Oct. 2014
Charge (mΩ)	29.1	32.2	28.1	26.7
Discharge (mΩ)	25.6	29.1	25.9	24.4
Temperature (°C)	23.6	20.1	23.3	25.6

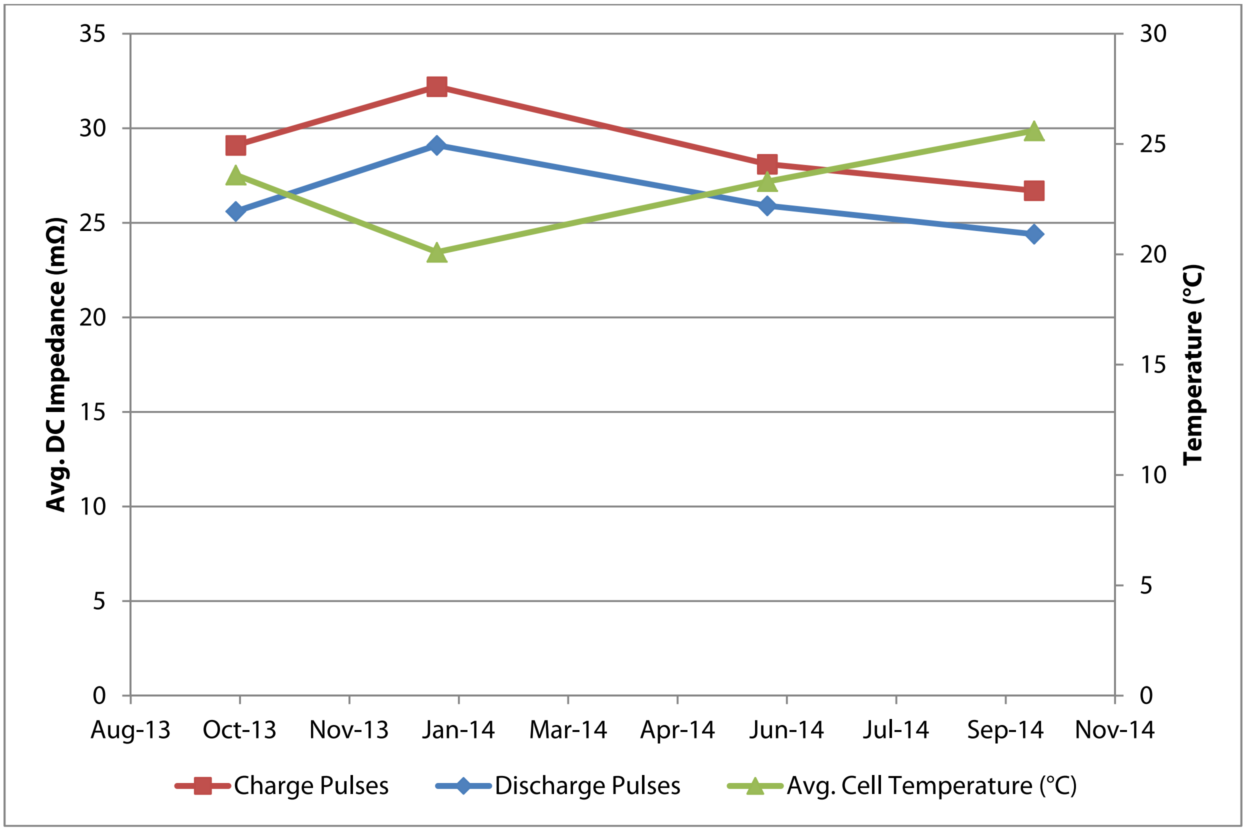

Figure 2: Average DC Impedance and Average Temperatures of Module Cells during REM Cycling

III. REM Cycling

In this long-term testing period, the A123 Module #5 was cycled under the REM duty cycle for a total of 202.7 days. The REM duty cycle was a prescribed 7-day duty cycle that was programmed in the Battery Control Software. Each time the duty cycle was run, the module was charged to 100% SOC[9] and then discharged to an SOC of approximately 72% prior to initiating the REM cycle. During the course of long-term REM cycling, the 7-day duty cycle was attempted a total of 34 times. Of those 34 attempts, there were only 16 times in which the module completed the full seven-day cycle (168 hours). Often times, the duty cycle would be stopped early due to the ABCs going offline or in order to utilize the module for testing python scripts via Paladin.

Where the module cells were not balanced before test initiation (approximately half of the REM cycling days), the min and max cell voltage limits were often reached during REM cycling. When this occurred, the Battery Control Software limited the flow of current in and out of the battery to prevent these limits from being exceeded (e.g. Figure 3). When this occurred, the prescribed REM power profile was not accurately achieved, though the impact of this on total kWh throughput was generally small. Previous analysis[10] has found that the module delivered 95.6% of the requested kWh discharge throughput where minimum cell voltage limits were encountered. When the module cells were balanced before REM duty cycle initiation, the minimum and maximum cell voltage limits were not exceeded during the course of running the 7-day REM duty cycle as seen in Figure 4.

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[9] As noted previously, REM cycles initiated before 4/25/2014 did not include cell balancing when charging to 100% SOC. REM duty cycles initiated on and after 4/25/2014 received cell balancing before bringing the module to its REM initiation SOC of approximately 72%.

[10] California Center for Sustainable Energy. First Long-Term Duty Cycle 60-Day Report; Regulation Energy Management (REM) Duty Cycle; Battery Module: A123 #5, Channel 1.Prepared for: National Renewable Energy Laboratory. February 2014.

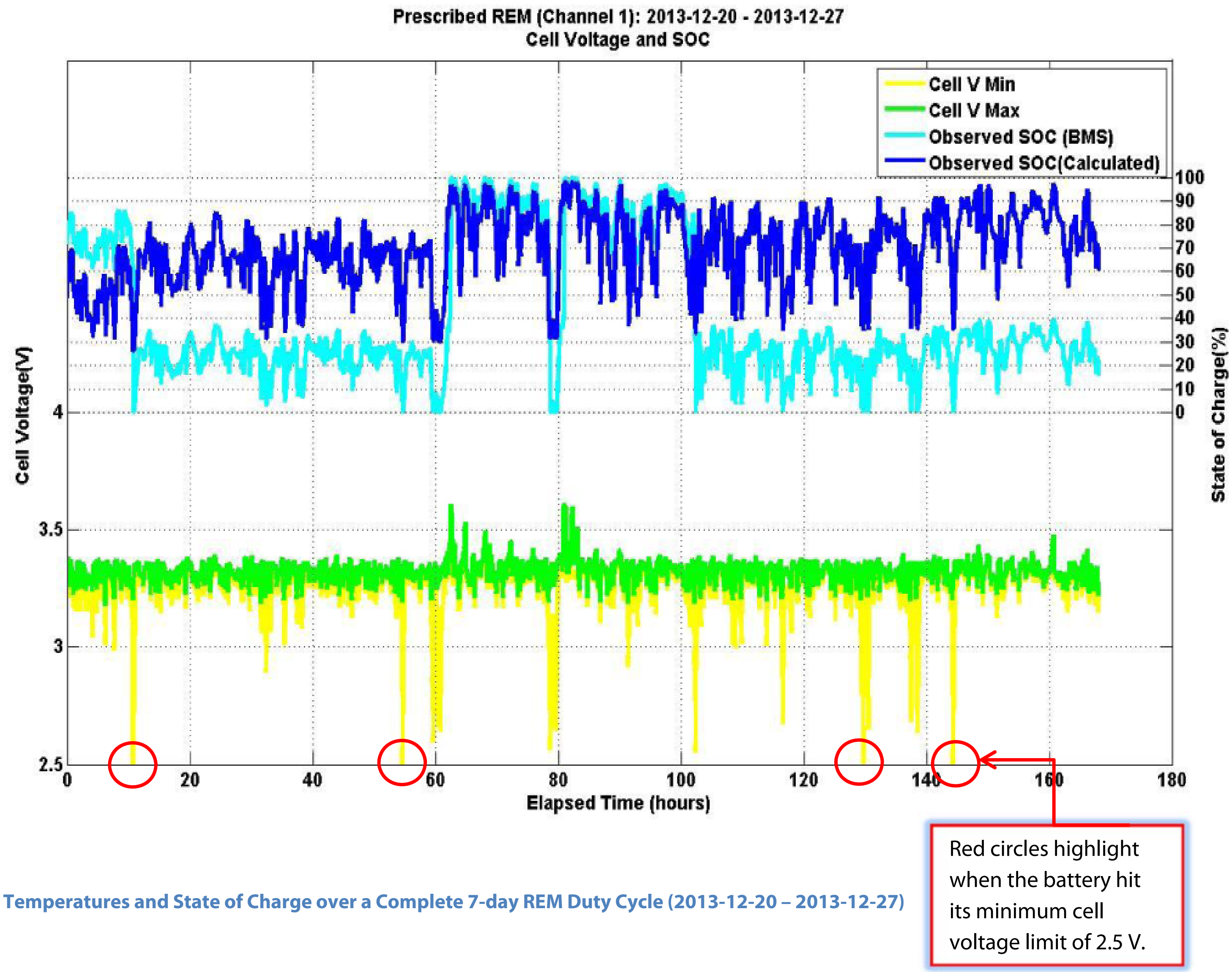

Figure 3: Cell Temperatures and State of Charge over a Complete 7-day REM Duty Cycle (2013-12-20 – 2013-12-27)

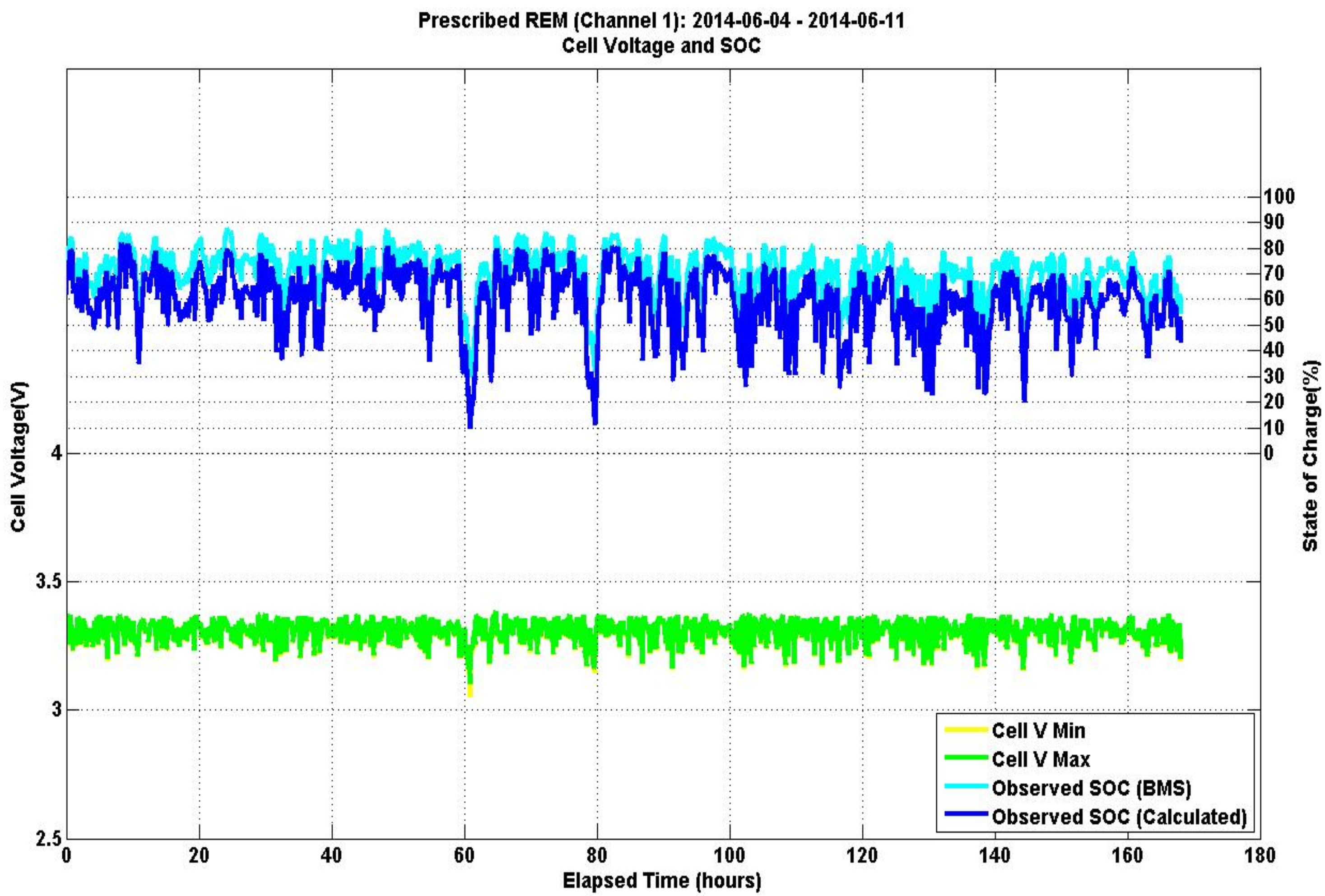

Figure 4: Cell Temperatures and State of Charge over a Complete 7-day REM Duty Cycle (2014-06-04 – 2014-06-11)

Table 4 below summarizes the effective one-way energy efficiency of a representative complete 7-day duty cycle run on the module during each of the REM cycling periods. The effective one-way energy efficiency of the module remains relatively constant between about 96-98% throughout long-term REM cycling, which agrees well with the RPT data that suggests module resistance is largely constant over the test period.

Table 4: Effective One-way Energy Efficiency of Module during each REM Cycling Period

	Period 1	Period 2	Period 3
Energy Efficiency	96.5	97.8	97.4

IV. Conclusions

We have learned about the performance of Lithium-ion battery modules, in particular the A123 Module #5, under long-term regulation energy management (REM) duty cycle testing. Performance of the module was measured by studying the module's ability to follow the duty cycle as requested by the intended REM power profile and via direct measurement of capacity, energy, and resistance using a Reference Performance Test (RPT).

The primary finding of this study is the large impact of cell imbalance on performance. During the first long-term REM cycling period where cell balancing was not employed, we observed a rapid rate of degradation in available capacity (0.66% capacity loss per GWh of REM discharge throughput) due to growing cell imbalance. This effect also impeded the packs ability to accurately deliver on the prescribed REM power profile.

When cell balancing was activated, as was the case during the entire third long-term REM cycling period, however, we observed a large increase in available capacity. This demonstrated the reversibility of the observed capacity loss due to cell imbalance. Subsequently, where cell balancing was regularly employed, the module consistently delivered the full prescribed REM power profile and the observed rate of capacity degradation was greatly reduced (0.06% capacity loss per GWh of REM discharge throughput).

The change in DC impedance of the module's cells is difficult to quantify because cell temperature was not controlled during the pulse characterization tests; however, the impedance measurements we have suggest insignificant change over the course of testing. Calculation of effective one-way energy efficiency under REM cycling supports this conclusion, as it varies by no more than 1.5% over the duration of testing.

Collectively, these results suggest that such Lithium-ion batteries could sufficiently handle the technical requirements of regulation energy management applications for at least one year following service in an automotive application, so long as cell balancing features are present and functional. Further, the low rate of capacity loss and negligible resistance growth could be linearly extrapolated to suggest an impressively long second-use REM service life. However, Lithium-ion battery degradation is known to be nonlinear; thus, additional testing is necessary to confidently assess the total REM service life.