The Effect of Variable End of Charge Battery Management on Small-Cell Batteries

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Abstract

Batteries are critical components for spacecraft, supplying power to all electrical systems during solar eclipse. These components must be lightweight due to launch vehicle limitations and the desire to fly heavier, more capable payloads, and must show excellent capacity retention with age to support the ever growing durations of space missions. ABSL's heritage Lithium Ion cell, the ABSL 18650HC, is an excellent low mass solution to this problem that has been proven capable of supporting long mission durations.

The NASA Glenn Research Center recently proposed and initiated a test to study the effects of reduced end of charge voltage on aging of the ABSL 18650HC and other Lithium Ion cells. This paper presents the testing details, a method to analyze and compare capacity fade between the different cases, and a preliminary analysis of the to-date performance of ABSL's cells. This initial analysis indicates that employing reduced end of charge techniques could double the life capabilities of the ABSL 18650HC cell. Accordingly, continued investigation is recommended, particularly at higher depths of discharge to better assess the method's potential mass savings for short duration missions.

Nomenclature

n	cycle number
EMF_{EOC}	cell electromotive force at end of charge
EMF_{EOD}	cell electromotive force at end of discharge
I_{BOC}	current at beginning of charge
I_{EOD}	current at end of discharge
R_{EOD}	internal cell resistance at end of discharge
V_{EOC}	terminal voltage at end of discharge
V_{EOD}	terminal voltage at end of discharge
ΔV_1	difference between terminal voltage and electromotive force at end of discharge
ΔV_2	difference between terminal voltage and electromotive force at beginning of charge
$\Delta SOC(n)$	change in state of charge of cycle n

I.   Introduction

Batteries make up a significant portion of the dry mass of a spacecraft, and are mission critical items that provide electrical power to all systems during periods of solar array shadowing. Solar array shadowing occurs naturally during missions due to eclipses of the sun by various heavenly bodies, most commonly the Earth and Moon. As space applications require lightweight technology due to the finite lift capacity of launch vehicles, all spacecraft components must be as light as possible. This has naturally driven the adoption of Lithium Ion battery technology thanks to its high specific energy.

In contrast to terrestrial applications where batteries (and even the powered devices themselves) are replaced frequently, space applications typically must undergo thousands of charge/discharge cycles over mission durations on the order of five to ten years. In order to meet battery requirements at End Of Life (EOL), the battery must have low degradation levels in terms of calendar and cycle life. Thus, in addition to mass and energy, ageing is a critical performance characteristic in judging a cell's suitability for space.

In response to these needs, ABSL has invested heavily in characterising the long-term performance of its heritage Lithium Ion cell, the ABSL 18650HC cell. Ongoing lifetests have passed the 40-million cell-hour point at various Depths Of Discharge (DOD), temperatures, and charge/discharge profiles simulating various space mission types (LEO, GEO, Interplanetary…). This data enables ABSL to make accurate long term performance predictions, vital to ensuring EOL power requirements are met, and has proven the ABSL 18650HC cell to be the an excellent candidate commercial cell in terms of calendar and cycle life. For example, ABSL's lifetest program has demonstrated that this cell can sustain more than 75,000 cycles, which is necessary for long duration LEO missions that accumulate more than 5,000 cycles per year. Based on this and other performances from ABSL's extensive lifetest program, the ABSL 18650HC has been selected for both LEO and GEO missions with target durations of 10 years. As life testing extends the confidence in the capabilities of the cell, ABSL expects these mission durations will continue to grow.

TABLE 1.—ABSL 18650HC SPECIFICATIONS

Parameter	Value
Cell	ABSL 18650HC
Dimensions	18 mm by 65 mm
Mass	42 grams
Maximum Cell Voltage	4.2 V
Minimum Cell Voltage	2.5 V
Nameplate Cell Capacity	1.5 Ah
Nameplate Cell Energy	5.4 Wh

Traditionally, ABSL has recommended charging the cell to its maximum voltage of 4.2 V. Accordingly, the majority of ABSL's lifetest data employs cycling to this end of charge voltage (EOCV). However, NASA Glenn Research Center (GRC) recently proposed and initiated a lifetest program to assess long term performance when cycling to reduced end of charge voltages (REOCVs) and verify the hypothesis that such charge management regimes could further improve cycling performance. This paper provides a report on the current status of these ongoing REOCV lifetests. First, ABSL's battery architecture, background on GRC's testing details, and a method to calculate and compare capacity fade between the multiple test cases is introduced. Then results from the first ~4000 cycles of the GRC test data are presented and discussed, along with a simple case study to assess the projected effect on mission durations when REOCV techniques are employed. Finally, conclusions regarding the benefits of REOCV operation are drawn and recommendations for future REOCV testing are made.

II.   The ABSL Battery Architecture

Traditional spacecraft batteries, based on Nickel Cadmium, Nickel Hydrogen, or Lithium Ion, consist of a single string of cells connected in series. This approach has three main drawbacks:

Reliability: A single point failure within a string of cells leads to a large step loss in voltage and energy (cell short circuit) or loss of the battery (cell open circuit).

Cost/ Parasitic Mass: Battery capacity requirements vary from mission to mission so that a fresh, qualified cell design is generally required. The cost of designing and qualifying a new cell design can be considerable. For occasions where qualified cell designs could be used for a new mission, it was commonly found that considerable excess mass had to be flown due to cell oversize.

Complexity: To overcome the problem of battery loss following an open circuit cell failure, cell bypass electronics had to be employed. Additionally, small batches of space-qualified cells vary in capacity due to slight manufacturing differences. As a result, charge-balancing electronics must be used to ensure full operational capability. Cell balancing and bypass electronics add complexity, cost and mass to the overall battery system.

ABSL's approach addresses these shortcomings by connecting a large number of highly uniform small cells incorporating protection devices at cell-level into an s-p cell topology, illustrated in figure 1. This strategy counters the typical space battery shortcomings, providing much improved reliability and simplicity while alleviating the need for complex external cell protection and charge-balancing electronics. These benefits have been proven by ABSL's extensive flight heritage, currently encompassing more than 4,000 cell years in space without failure and the launch of 26 vehicles powered by ABSL, including Proba, the longest operating Lithium Ion powered spacecraft at 5.5 years and counting in LEO. It also allows ABSL to offer a large degree of flexibility and scalability in its batteries, plus the opportunity to optimize total battery mass to any specification, thanks to the small unit size of each cell.
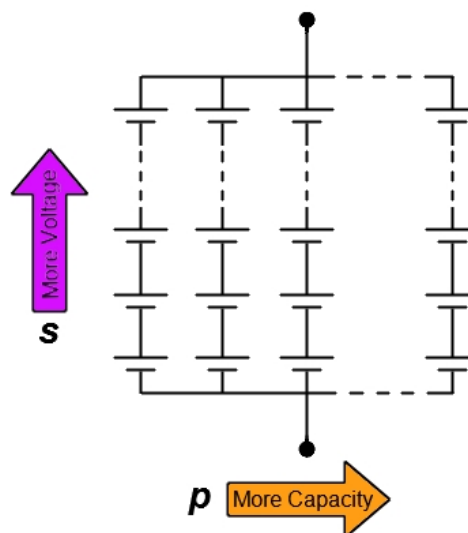

Figure 1.—ABSL's s-p Topology
In ABSL's s-p topology, a large number of small cells are first connected in strings of length 's' to meet voltage requirements, then 'p' strings are connected in parallel to meet capacity requirements.

III. Testing Background

GRC commissioned a test of batteries from ABSL and other suppliers to assess the performance of Lithium Ion cells over a wide range of LEO conditions. The data generated will be used to build an empirical model to predict the performance and cycle life of Lithium Ion batteries operating at a specified set of mission conditions. Using this tool, mission planners will be able to design operation points of the battery system while factoring in mission requirements and the expected life and performance of the batteries.

Test conditions were selected via a statistical design of experiments to span a range of feasible operational conditions for LEO aerospace applications. The variables under evaluation are temperature, DOD, and EOCV. One of the purposes of the testing is to assess the effects of reduced EOCV cycling on capacity fade. The tests were carried out by Crane, a division of the Naval Surface Warfare Center, and are currently on-going. Twenty 4s2p modules using the 18650HC cell were built by ABSL and delivered to Crane (fig. 2), who then assembled the twenty 4s2p modules into ten 4s4p modules.

The test sequence for all modules went as follows: (1) Open Circuit Voltage (OCV) decay testing, (2) capacity measurement, (3) reduced EOCV cycling, though module 1 alone underwent additional capacity measurements at a range of temperatures prior to this sequence. OCV decay testing was done at 22 °C and 4.1 V per cell over a period of one week. Capacity was measured at 20 °C by charging at C/5 to 4.1 V per cell, taper charging to C/50, then discharging at C/2 to 3.0 V per cell. The value used for C was determined by the capacity measured from the previous cycle, and cycles continued until the change in capacity between iterations was less than 1 percent.

Figure 2.—ABSL 4s2p Modules
ABSL provided 20 4s2p batteries to GRC, which were wired in parallel to yield 10 4s4p batteries for REOCV testing.

All reduced EOCV cycling was performed on a real-time LEO time scale (55 min for charge, 35 min for discharge) at varying DODs, temperatures, and EOCVs. In each case, the amount of capacity removed in Ah was calculated using the average of the measured total capacities of all modules and the selected DOD in percent. The necessary discharge rate was calculated by dividing the amount of capacity removed by the 35 min discharge period. The charge rate was calculated using 110 percent of the removed capacity and the 55 min charge period, allowing for a short taper charge once the module reaches its selected cut-off voltage. The range of DODs, temperatures, and EOCVs is presented below in table 2.

TABLE 2.—TEST CASES AND CONDITIONS

Cell EOCV, V	Temperature, °C	DOD, %	Charge, C	Discharge, C
4.05	30	20	0.22	0.34
4.05	10	30	0.33	0.51
4.05	20	40	0.44	0.69
4.05	10	40	0.44	0.69
3.95	20	20	0.22	0.34
3.95	30	30	0.33	0.51
3.85	10	20	0.22	0.34
3.85	30	20	0.22	0.34
3.85	20	30	0.33	0.51
3.85	30	40	0.44	0.69

Every 1000 cycles an operational capacity measurement is performed. Here the battery is cycled between an EODV of 3.0 V per cell and EOCV equal to that used in cycling. Similarly, the same temperature and charge and discharge rates as are used in cycling are maintained during the operational capacity measurement.

IV. State of Charge Capacity Fade Analysis

The wide range of conditions (temperature, DOD, EOCV, etc.) provide the opportunity to look at a wide range of operational conditions and understand in better detail the effects of reduced EOCVs, but unfortunately, due to the manner in which the statistical design of experiments for the test program was created, there is no straightforward means of comparing capacity fade between different cases. Directly comparing the rate of decline of EODVs is not useful for comparing capacity fade due to the varied DODs and EOCVs. Likewise, the operational capacity measurements are difficult to compare due to the difference in EOCV, temperature, and rates from one case to another, and only a few operational capacity measurements have been made to date.

To overcome these obstacles, a method was developed to identify capacity fade independent of cycling conditions and operational capacity measurements. The basis of the method lies in identifying the state of charge (SOC) at EOC and EOD, calculating the change in SOC for each cycle (ΔSOC), then correlating the growth in ΔSOC over time to the remaining capacity of the battery. Details of the method are described below.

First, internal cell resistance at EOD is calculated using recorded voltage and current data. At EOD the cell's terminal voltage makes a sharp jump when the current switches from negative (discharge) to positive (charge) as seen in figure 3. Of course, the cell's electromotive force (EMF), which is directly tied to its SOC, makes no such jump. Thus, the change in voltage is strictly a function of the change in current and the cell's internal resistance, the latter of which can be calculated via eq. (1).

$$R_{EOD} = \left(\Delta V_1 + \Delta V_2 \right) / \left(I_{BOC} - I_{EOD} \right) \tag{1}$$

Next, knowing the cell resistance, terminal voltage, and current at EOD, the EMF at EOD can be calculated using eq. (2). For the data presented in this study, the EMF at EOC is assumed equal to the terminal voltage at EOC. This assumption brings a smaller error relative to the same assumption at EOD due to the lesser difference between terminal voltage and EMF at EOC, thanks to lower current levels at EOC and a reduced cell resistance at high SOC. However, a similar process can be used to account for these differences and will be employed in future work.

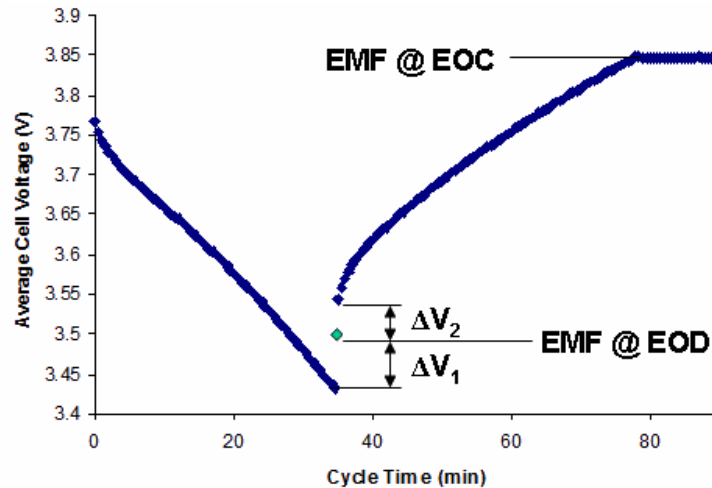$$EMF_{EOD} = V_{EOD} - I_{EOD} R_{EOD} \tag{2}$$

Figure 3.—Cell Level Terminal Voltage at EOD
The jump in cell terminal voltage when switching from discharge to charge is used to calculate EOD cell resistance, then the value of the cell EMF at EOD.
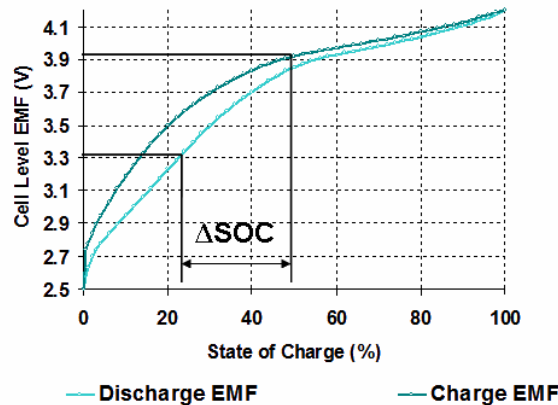

Figure 4.—Calculating ΔSOC from the EMF versus SOC Curve
The EOC and EOD EMF values can be used to calculate the change in SOC for any given cycle with accurate knowledge of the EMF versus SOC curves.

The third step is translating the EMF values at EOC and EOD to their corresponding SOC values. With accurate knowledge of a cell's EMF versus SOC curve, these values are readily obtained. However, as it is well known that Li-Ion cells have different relations between EMF and SOC for both charge and discharge, it is important that the EMF at EOC is applied to the *charge* EMF curve to calculate SOC at EOC, and likewise that the *discharge* EMF curve is used at EOD. Then, with the EOC and EOD SOCs in hand, the change in SOC for the corresponding cycle (ΔSOC) can be calculated by subtracting the latter from the former as illustrated in figure 4.

The above method is first applied to compute ΔSOC for a reference cycle early in life, preferably the first cycle. Then by applying these same steps to each subsequent cycle, the retained capacity over life can be calculated by comparing the change in ΔSOC using eq. (3). Calculating retained capacity in this manner provides a measurement of capacity fade that allows the direct comparison of multiple cases regardless of EOCV, DOD, rates, temperatures, etc.
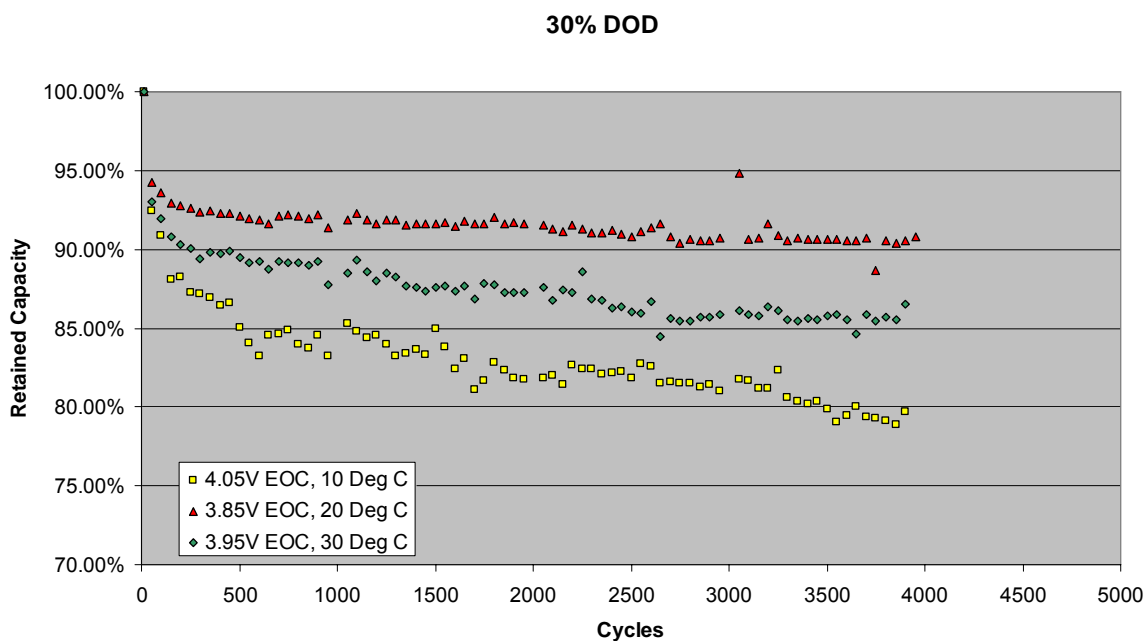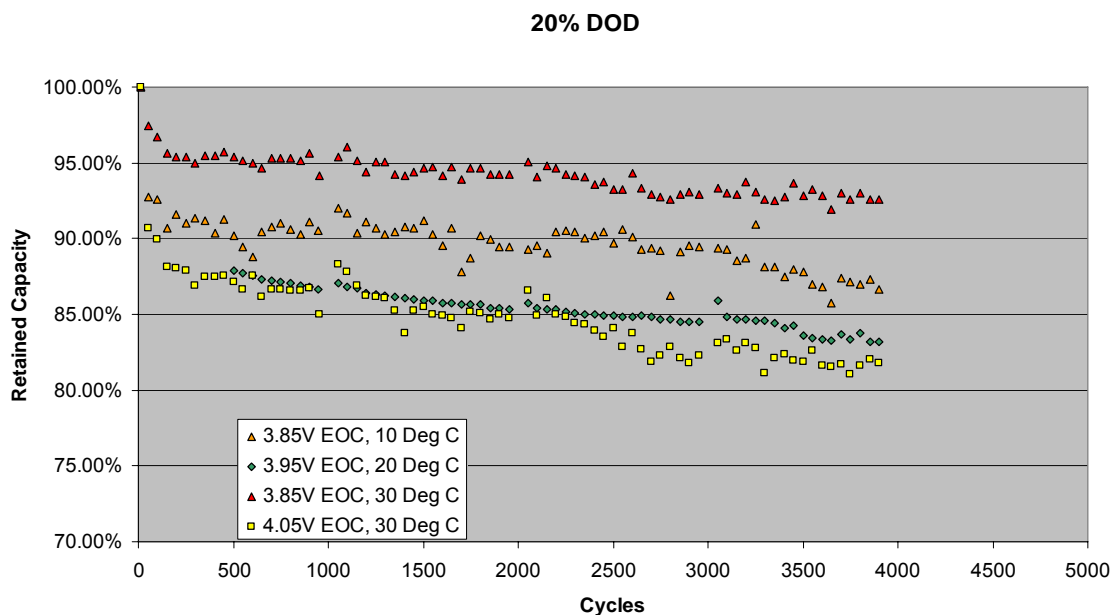
$$\text{Retained Capacity}\,(n) = 100\% * \Delta SOC(1)/\Delta SOC(n) \qquad (3)$$

It is important to note that accurate knowledge of the EMF versus SOC curves over life and across the range of investigated temperatures is crucial. This analysis can be applied to ABSL 18650HC cycling data with confidence only as ABSL has very well characterized this cell's behavior, showing the changes in temperature and age relevant to this study to have negligible effects on the EMF versus SOC curves.

V.   Analysis of Results

The SOC analysis method discussed above has been applied to all of the GRC test cases. The resultant retained capacity plots are presented below in figures 5 to 7, grouped by DOD. Note that in each plot lower EOCVs always outperform higher EOCVs, regardless of temperature.

Figure 8 summarizes the above results, showing the retained capacity after 3,900 cycles for each case. Here it is clearly evident that the lower EOCV cases show better capacity retention. With regard to temperature and DOD, it appears that this data does not always behave as has been witnessed at 4.2 V EOC, with lower temperatures and DODs supporting superior capacity retention over life. However, drawing conclusions on the effects of temperature and DOD is difficult due to the limited number of test cases and the inability to decouple these two factors.
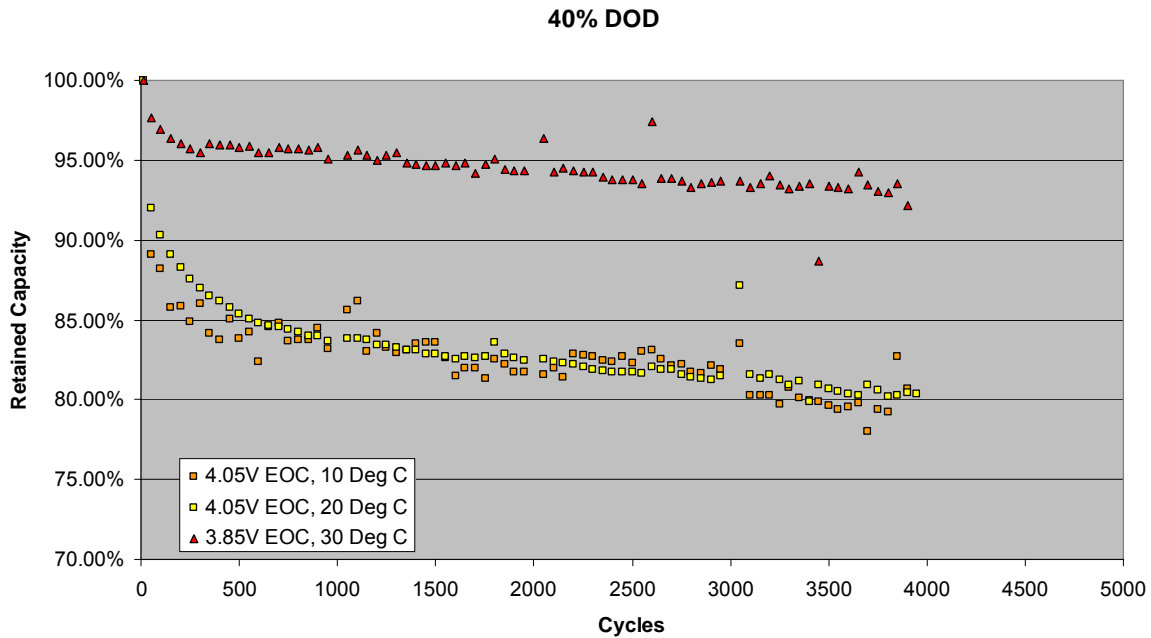
20% DOD

Figure 5.—Retained Capacity Over Life at 20 percent DOD

30% DOD

Figure 6.—Retained Capacity Over Life at 30 percent DOD

40% DOD

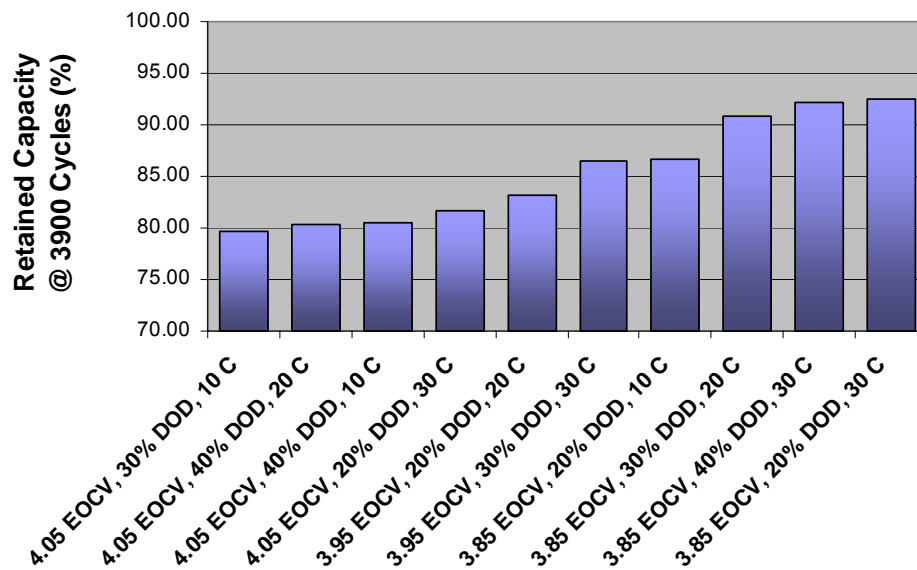Figure 7.—Retained Capacity Over Life at 40 percent DOD

Figure 8.—Retained Capacity After 3900 Cycles
Results show clearly that lower EOCVs offer improved capacity retention; however, trends with DOD and temperature are unclear and may contradict traditionally witnessed long term behaviors.

On the other hand, in similar fashion to cell behavior at 4.2 V EOC (fig. 9) all of these cases are characterized by a region of relatively steep, non-linear capacity fade during initial cycling (commonly known as burn-out), followed by a second region displaying a slower, linear fade rate. For the data presented here, the combination of the steep capacity fade during burn-out and selecting a reference cycle as the first REOCV cycle can exaggerate the effects of small differences in initial capacity and pre-REOCV cycling conditions (including storage and preliminary testing) between cases. As an example, consider moving the reference cycle for the 30 percent DOD / 3.85 V EOC / 20 °C from its current value to one 50 cycles later – the resultant plot would show approximately 6 percent less fade across the board. Thus, slight errors in reference cycle selection (namely, when the pre-reference-cycle histories for multiple cases are not *exactly* equivalent) in the burn-out region can dramatically distort comparisons of absolute retained capacity values, though the slopes of the linear regimes are largely unaffected.
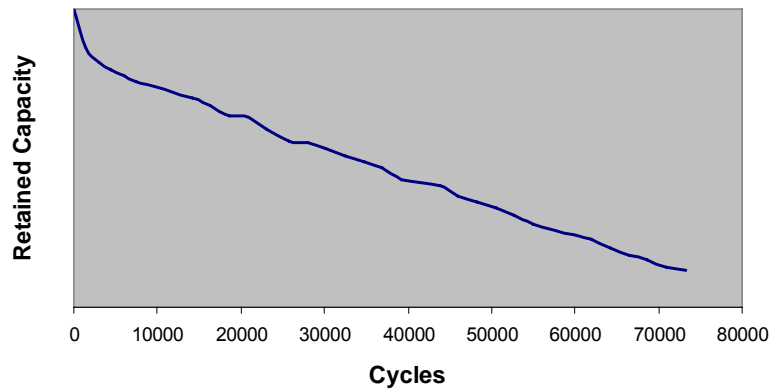
Figure 9.—Capacity Fade at 4.2V EOC

Results at 4.2 V EOC show similar trends to the data at reduced EOC voltages.
In all cases, a steep, nonlinear initial fade region known as burn-out occurs,
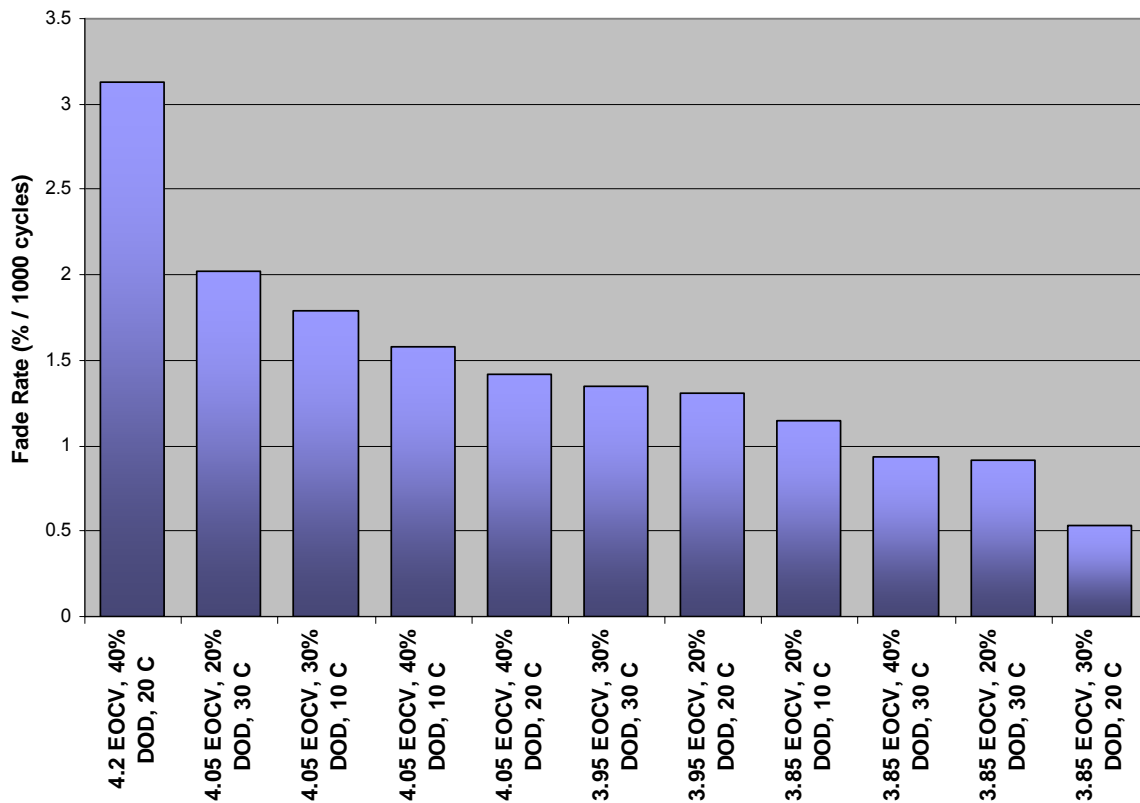*followed by a linear region with a much reduced fade rate.*

Figure 10.—Steady State Fade Rate

This plot shows a comparison of steady state fade rates, where the errors associated with selecting a reference cycle
in the SOC capacity fade analysis method have been reduced. The results continue to show a substantial
performance improvement at lower EOCVs and more traditional temperature and DOD trends.

To reduce the sensitivity to reference cycle selection induced by the burn-out region, an analysis of the steady state fade rate was undertaken. Here the reference cycle was selected as the 501st cycle to ensure that the burn out region had been surpassed. Then, linear trend lines were fit to each case, and their slopes collected in figure 10. As before, there is a clear progression towards less fade with lower EOCVs. Interestingly, these results show a change in trends with DOD and temperature from the results in figure 8. This could be a result of the analysis method's reference cycle sensitivity, or it could indicate that changes in temperature and DOD have different effects on the burn-out regime than they do on the subsequent linear fade regime. At this point there is not sufficient data available to identify the true cause.
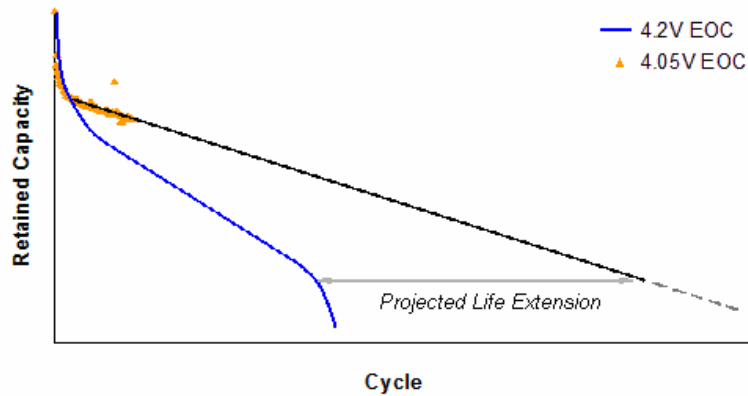
Figure 11.—Comparison of Life for Traditional and REOCV Charge
Management Techniques at 40 percent DOD
*Assuming that REOCV cases show similar fade trends over life to that of
4.2 V EOC cases, battery life could be doubled for 40 percent DOD cases.
Given the cycle life exhibited by the ABSL 18650 HC cells – proven
capable of more than 75,000 cycles – the combination of
REOCV techniques and ABSL batteries could
support extremely long missions.*

VI.   40 Percent DOD Case Study

For comparison to traditional charge management architectures, results from a SOC analysis of a real time LEO life test at 4.2 V EOCV, 40 percent DOD, and 20 °C for the same cell type have been included in figure 10. This plot shows that, relative to the most similar REOCV case, reducing the EOCV from 4.2 to 4.05 V reduces the steady state fade rate by a factor of two.

At 4.2 V EOC, these cells display three distinct fade regions over life: a relatively steep and nonlinear fade region early in life, a shallow, linear fade region through mid-life, and a transition to a steep linear region at end of life. Assuming the cells behave similarly at 4.05 V EOC, the extrapolation in figure 11 reveals that life could be approximately doubled for 40 percent DOD cases. Adding in the fade rate benefits at lower EOCVs, combined with the ability to progressively raise EOCV levels over time as minimum EODV levels are met, mission lifetimes could be further extended by the use of REOCVs.

VII.   Conclusion

This paper has presented the to-date REOCV lifetesting performed by GRC, and proposed a method to calculate capacity fade and compare performance between the varied cases. Results from the first 3,900 cycles show substantial benefit from even slight reductions in EOCVs, which could double the current lifetime capabilities of the ABSL 18650HC Lithium Ion cell. However, as the amount of accumulated data is small relative to the projected lifetime, it is recommended that analysis of GRC's REOCV data continue to ensure the improved fade rates persist with additional cycling. Further experimentation, particularly at higher DODs, is also recommended to accurately assess the possible mass savings this method could bring for short duration missions.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
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