International Space Station Nickel-Hydrogen Extended Battery Discharge Model Analysis

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One goal of the Power and Propulsion office at NASA Glenn Research Center is to accurately model the Electrical Power System performance of the International Space Station. For that purpose, a computer simulation named System Power Analysis for Capability Evaluation (SPACE) is used. This paper discusses a new technique in SPACE to model extended battery discharge conditions on the space station. An extended discharge condition is the process during which a battery is discharged beyond the normal discharge cycle. Such a condition may occur during periods of space station operation in which the arrays are significantly off-pointed and unable to generate sufficient power, or during periods of exceptionally high electrical load demand, causing the batteries to continue discharging in the sun period to meet that demand. During extended discharge, a battery can reach low enough voltages such that the power channel may shut down, leaving no power for the loads on that channel. Thus, it is important to be able to accurately predict when the battery cell voltage will fall too low, so that mission planners and mission operators will be able to take countermeasures. One way to model extended battery discharge is to linearly extrapolate the battery discharge curve. Another method is to create several baseline extended discharge curves from test data at certain conditions, and perform time based interpolation of the curves to determine the extended discharge voltage curves for other conditions. A new extended battery discharge modeling method was created to improve model accuracy as compared to the two alternative methods. The new method uses one curve to represent the extended battery discharge voltage for all different conditions. The longest baseline curve at 20% depth of discharge, 10A, and 0°C is shifted by time and truncated to generate the extended battery discharge curves at other conditions. This method has been verified against the voltage curves used in the Space Systems Loral battery performance model with a worst case correlation coefficient of 0.9564.

Nomenclature

I = Current (A)
I_{EOD} = End of Discharge current (A)
$I_{extended\ discharge}$ = Extended discharge current (A)
R^2 = Correlation coefficient
t = Time from beginning of eclipse (min)
Tend = Time at which the voltage of the Space Systems Loral extended discharge curve reaches 1 volt (min)
$Toffset_{DOD}$ = Offset time with varying battery depth of discharge (min)
$Toffset_{Temp}$ = Offset time with varying temperature (min)
$Toffset_{Total}$ = Total offset time (min)
V = Cell voltage (V)
V_{adj} = Voltage adjustment for extended discharge curve to be compatible to the discharge curve (V)
V_{EOD} = End of discharge voltage (V)

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Introduction

The International Space Station (ISS) Electrical Power System (EPS) utilizes Nickel-Hydrogen (Ni-H2) batteries to store energy obtained from the photovoltaic arrays during insolation, primarily for use during eclipse, and also on the occasion when the load demand exceeds the array output when the ISS is not in eclipse. For example, when the arrays are not sun tracking due to assembly and maintenance operations, docking and undocking, or shuttle waste water dump, the load demand can exceed array output. The ISS will augment array power with battery power. One battery consists of two Orbital Replacement Units (ORUs) connected in series, and each ORU contains 38 individual pressure vessel Ni-H2 battery cells, as shown in Figure 1. More detailed information on the batteries can be found in Dalton and Cohen 2002.[1,2,3]

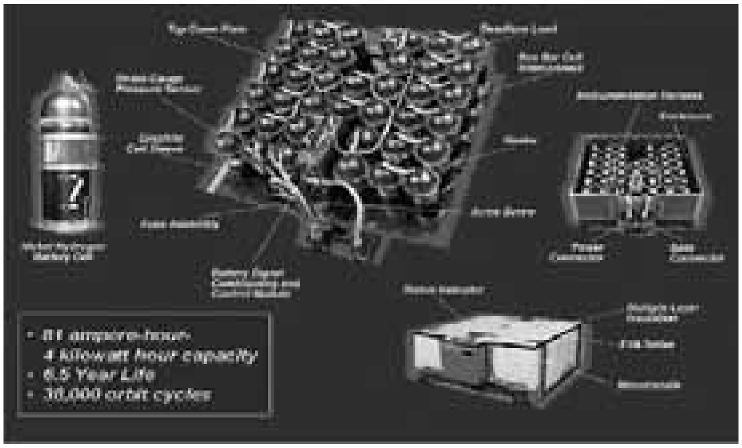


Figure 1. ISS Battery Subassembly Orbital Replacement Unit.

The batteries are designed to operate at 35% depth of discharge (DOD) during normal operation. The batteries currently on-orbit, however, have experienced an average DOD of about 24%. As more hardware is brought up to the station, the power demand will increase and the battery DOD will increase accordingly. Also, the DOD experiences orbit to orbit variations due to minute by minute changes in power demand. Because the batteries will experience varying DODs during their lifetime, modeling the actual changes in DOD is too cumbersome; thus battery life fraction is used. The Life Fraction (LF) of a battery is the fraction of the battery's life that has been "used up" between the beginning of life (BOL) and end of life (EOL) of a battery, such that at BOL, LF = 0 and at EOL, LF = 1. End of life is defined as the time at which the end of discharge voltage (V_{EOD}) is equal to 1.0 volt per cell at a 35% DOD.

At its current altitude of approximately 200 nautical miles, the ISS takes about 92 minutes to complete one orbit around the Earth. A normal battery cycle consists of discharge during eclipse, and charge during insolation. Depending on exact orbit conditions, eclipse period can range between 0 and 36 minutes, with the corresponding insolation period between 56 minutes to 92 minutes in a full sun orbit. The exact time is a function of orbit mechanics. Typical battery cycling operation is shown in Figure 2. In this plot derived from ground test data, the voltage increases during charge and decreases sharply during discharge. When the battery is nearly fully charged, the voltage decreases slightly during taper charge. The gray bars represent eclipse periods.

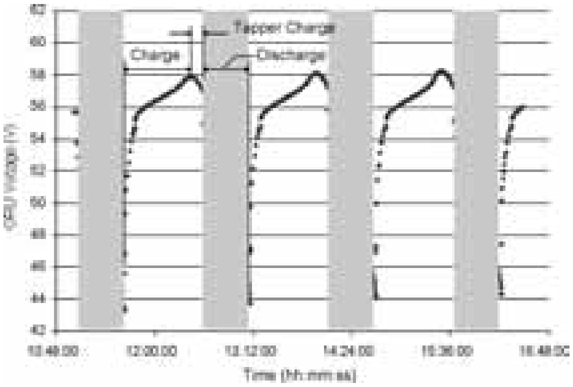


Figure 2. Typical ORU charge/discharge cycles.

There are cases, however, where the battery will continue to discharge after the space station emerges from eclipse. For example, when space station solar panels are parked to accommodate assembly operations or shuttle and Soyuz docking and undocking, the arrays may be significantly off-pointed and unable to generate sufficient power, such that the batteries must continue to discharge in the sun period to meet the electrical load demand. The battery discharge will continue until the electrical load demand can be met by the solar arrays or the battery discharge voltages become too low. The process during which a battery is discharged beyond the normal discharge cycle is termed "extended battery discharge."

Although extended battery discharge is not a common occurrence, it is important to be able to model it accurately because during extended discharge, a battery can reach potentially unfavorable voltages. If the battery discharge voltage drops too low, the ISS EPS software will then begin a series of load sheds starting at 82V, by turning off various pieces of equipment/loads in a preselected priority. The EPS hardware, on the other hand, is designed to accommodate battery discharge voltages as low as 76 volts. If the battery discharge voltage falls below this level, the battery would effectively be commanded to shut down. Thus it is useful for the mission planners and mission operators to be able to predict exactly when the voltage of the battery cell will fall to these levels as well as when the battery will reach the EOL condition.

Space Systems/Loral developed a battery performance model program for NASA that includes handling of extended discharge orbits based on ground test data.[4] The System Power Analysis for Capability Evaluation (SPACE)[5,6] computer model was created by NASA Glenn Research Center to predict the performance of the ISS electrical power system. SPACE, which has been validated using on-orbit data[7,8] except for the extended battery discharge portion, incorporates a modified Space Systems Loral battery performance model.

ISS Battery Models

SPACE Battery Model Overview

Following the Space Systems Loral battery modeling techniques, SPACE models battery charge voltages, discharge voltages, and columbic efficiencies by interpolating curves between BOL and EOL at three DODs and three temperatures (20%, 35%, and 60% DOD; 0°C, 10°C, and 20°C). Currently, the space station batteries operate in the 0°C to 5°C temperature range. Weighting factors are used to interpolate between BOL and EOL. The BOL discharge voltage is used for the first 40% of the battery life; after that, the EOL weighting factor increases exponentially from zero such that the voltage eventually drops to the EOL value.

Figure 3 shows the discharge and charge voltages at the three DODs for 0°C used in the Space Systems Loral 2001 battery performance model. Note that the discharge voltages generally drop from BOL to EOL, and the end of discharge voltage at EOL is 1 volt for all cases, as defined. The charge voltages do not change very much throughout life, but are generally higher toward EOL. Figure 4 demonstrates the drop in charge efficiency as state of charge (SOC) increases. Lower charge efficiencies also result from high life fractions and high DODs.

For modeling purposes, battery degradation is accounted for by reducing charge efficiency, reducing discharge voltage, increasing charge voltage, and increasing internal cell resistance. ISS battery ORU life testing results, shown in Figure 5, demonstrate the effects of long term degradation of discharge voltage. Notice that in Figure 5, a periodic battery reconditioning was performed starting at approximately cycle 27,000, resulting in a temporary increase in V_{EOD}.

SPACE Handling of Extended Battery Discharge

The SPACE version 3.2 battery model did not specifically model extended battery discharge, because it was treated as an extension of the battery discharge period. SPACE linearly extrapolated the last two points of the eclipse discharge voltage curve, as shown in Figure 6 to model the extended battery discharge. After the first photovoltaic module was activated in December 2000 and on-orbit data became available, it was noted that the on-orbit extended battery discharge was not a linear function. Therefore, the SPACE Team at NASA Glenn Research Center investigated extrapolating the Space Systems Loral battery model in the extended discharge region.

Space Systems Loral Extended Battery Discharge Model

From test data, Space Systems Loral created 27 baseline battery discharge curves for each of the following parameter combinations: DOD of 20%, 35%, and 60%, temperature at 0°C, 10°C, and 20°C, and current of 10A,

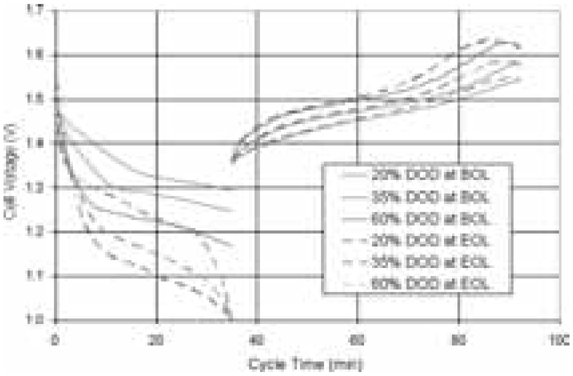


Figure 3. Space Systems Loral battery model discharge and charge cycle at BOL and EOL, at 0°C.

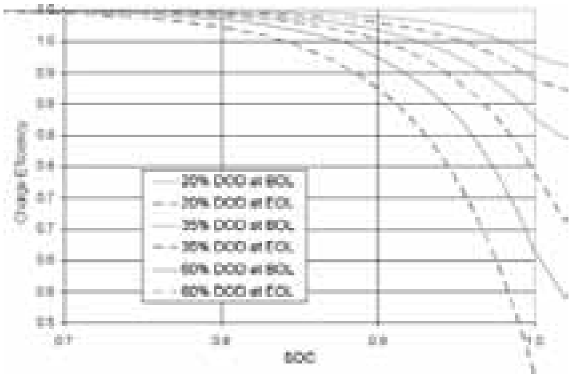


Figure 4. Space Systems Loral battery performance model charge efficiency as a function of state of charge (SOC) at BOL and EOL, 10°C.

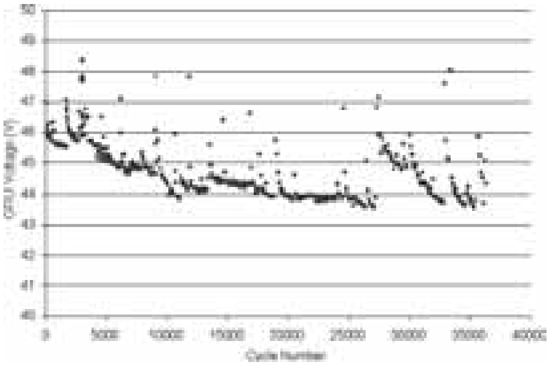


Figure 5. ORU V_{EOD} showing long term battery degradation.

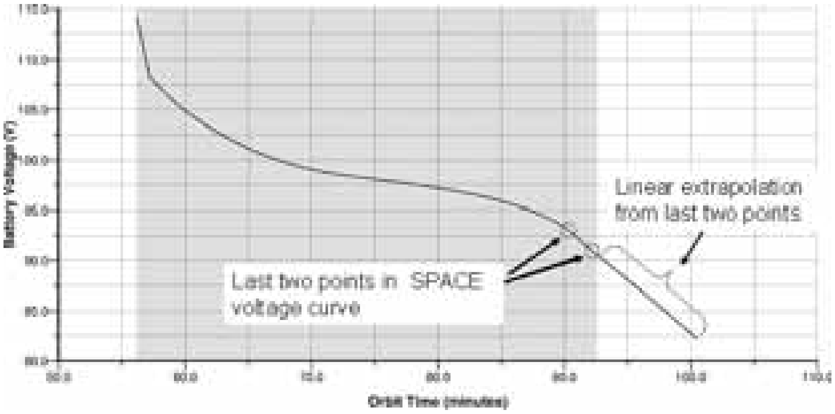


Figure 6. Illustration of SPACE battery discharge voltage linear extrapolation of extended battery discharge.

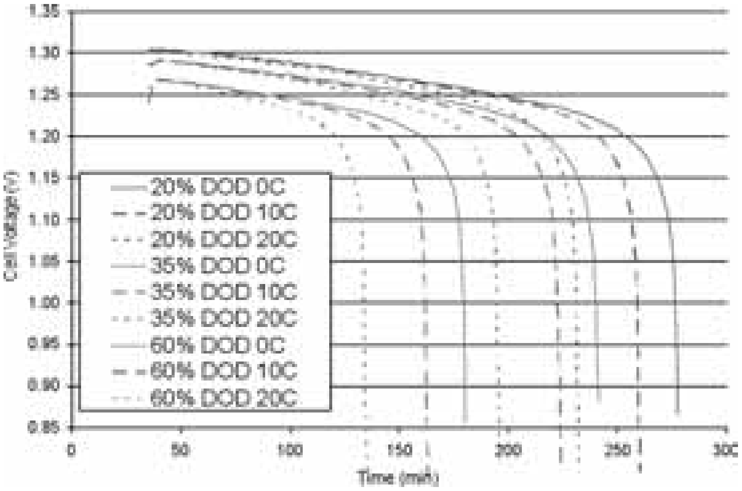


Figure 7. Space Systems Loral ground test data: baseline curves at 20A.

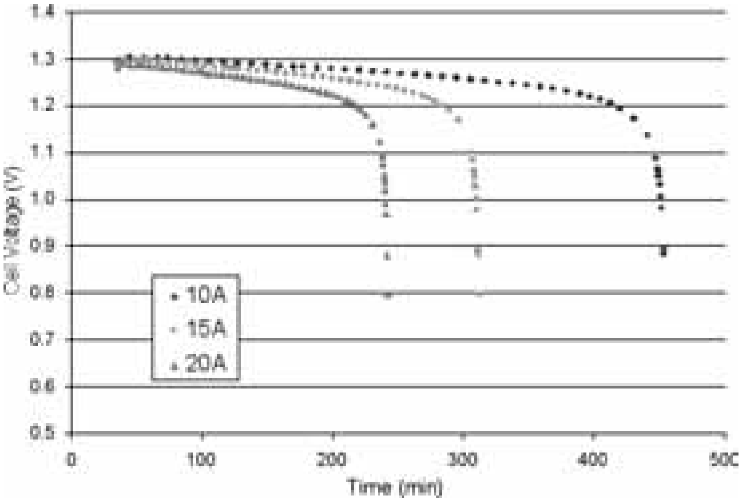


Figure 8. Space Systems Loral data: baseline curves at 35% DOD and 0°C.

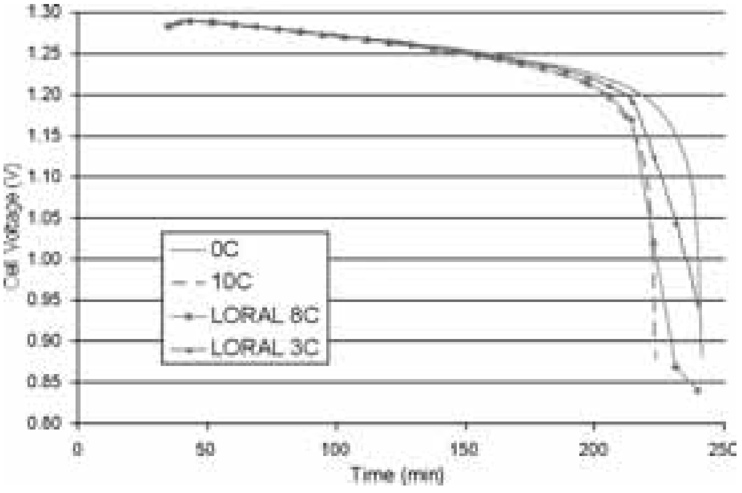


Figure 9. Examples of 3°C and 8°C curves obtained via interpolation from 0°C and 10°C Space Systems Loral temperature baselines at 35% DOD and 20A.

15A, and 20A. Figure 7 shows the nine baseline curves at 20A, and Figure 8 shows the three baseline curves at 35% DOD and 0°C.

From the 27 baseline curves, the Space Systems Loral model performs a series of interpolations. Upon investigation, three voltage curves are interpolated based on time. To determine the extended discharge voltage curve for a specific temperature, the corresponding voltages from two baseline temperature curves were interpolated at a fixed point in time.

The specific case in Figure 9 shows the interpolation between a 0°C curve and a 10°C curve to obtain the 3°C and 8°C curves. The interpolation looks reasonable until about 180 minutes, when the baseline curves begin to drop in voltage and the interpolated 3°C and 8°C curves begin to deviate from expected behavior. One would expect the 3°C and 8°C curves to have shapes similar to the baseline curves, and drop in voltage at proportional times. However, these examples show that the 8°C curve drops almost at the same time as the 10°C curve, and the 3°C curve reaches 1.12 volts much earlier than expected. Thus, the time-based interpolation does not correctly capture the voltage drop, showing that this method breaks down outside its applicability region.

A similar problem occurs with interpolation and extrapolation of extended battery discharge curves at different currents. The three baseline currents are 10A, 15A and 20A. To generate an extended discharge voltage curve for 30A, the Space Systems Loral model extrapolates the 15A and 20A curves at each time point (see Figure 10).

Examining Figure 10, the 10A, 15A, and 20A curves each reach 1 volt at 416, 275, and 205 minutes after eclipse respectively. By applying a power regression extrapolation to these values, Equation 1a, the 30A curve would be expected to reach 1 volt at approximately 136 minutes (Eq. 1b) after eclipse. In Figure 10, the time corresponding to 136 minutes after eclipse is 171 minutes, which is the sum of the eclipse time plus the above time to reach 1 volt (136 min + 35min = 171 min).

$$\textit{Time to reach 1 volt after the end of eclipse} = 4350.9\,(I)^{-1.0198} \tag{1a}$$

$$136\text{min} = 4350.9\,(30A)^{-1.0198} \tag{1b}$$

Due to the time based extrapolation method, however the 30A voltage curve, as shown in Figure 10, does not reach 1 volt until time = 225 minutes, or 190 minutes after eclipse. Extrapolation by time prevents the 30A curve from dropping before the 20A curve drops.

Table 1: Space Systems Loral Battery Model Method for Calculating Time Offset

DOD	Time Offset (min)
20%	(TEND – 35) · 0.98392 · LF
35%	(TEND – 35) · 0.94905 · LF
60%	(TEND – 35) · 0.84382 · LF

Space Systems Loral battery model accounts for the life fraction of the battery by shifting the extended discharge voltage curve by an offset time. After the curve is shifted, then all the points of the voltage curve, prior to the end of the eclipse, are eliminated. The method for calculating this offset time is given in Table 1. The variable T_{end} is the time at which the voltage of the Space Systems Loral discharge curve reaches 1 volt, assuming time equals zero is at beginning of eclipse. Figure 11 shows an example of the cell voltage output by extrapolating from the Space Systems Loral battery model into the extended discharge region for two different life fractions. The shaded region in Figure 11 indicates the initial eclipse period followed by an extended discharge.

Upon completing the Space Systems Loral model time based interpolations, the resulting voltage versus time extended battery discharge curve is then adjusted. The initial voltage in the extended discharge phase is matched to the end of eclipse voltage, assuming both voltage curves use the same current. If the extended discharge current is different, voltage adjustments are made based on the cell internal resistance, as shown in Equation 2.

$$V_{adj} = R(I_{EOD} - Iextended\ discharge) \qquad (2)$$

Proposed Extended Battery Discharge Models

Extrapolating both the SPACE battery model and the SS/L battery model into the extended battery discharge region did not work well. Neither the SPACE nor SS/L battery models were designed to handle extended battery discharge.

Interpolation by Voltage

Given the deficiencies of interpolating by time for extended discharge voltage curves, the first proposal was to interpolate by voltage. The sharp voltage drop at the end of the interpolated curve would be improved by this technique; however, the beginning of extended discharge where voltage is relatively level would not be correctly interpolated.

Logarithmic Regression

Polynomial, logarithmic, power, and exponential regression lines were also used to try to describe the baseline voltage curves. From the shape of the curves and mathematical analysis, it appears that logarithmic regression was the most appropriate, and that all the regression lines had the same format. The regression form in Equation 3 produced correlation coefficients, R^2, greater than 0.95 when correlating with the baseline curves created by Space Systems Loral.

$$V = (0.041 \pm 0.005)\ln(-t + Tend) + V_{adj} \qquad (3)$$

The small variation in the coefficient before the logarithm indicates that all of the extended battery discharge curves generally have the same shape. This realization led to the creation of the combined shifting method for extended battery discharge modeling, which has replaced the linear extrapolation method in SPACE.

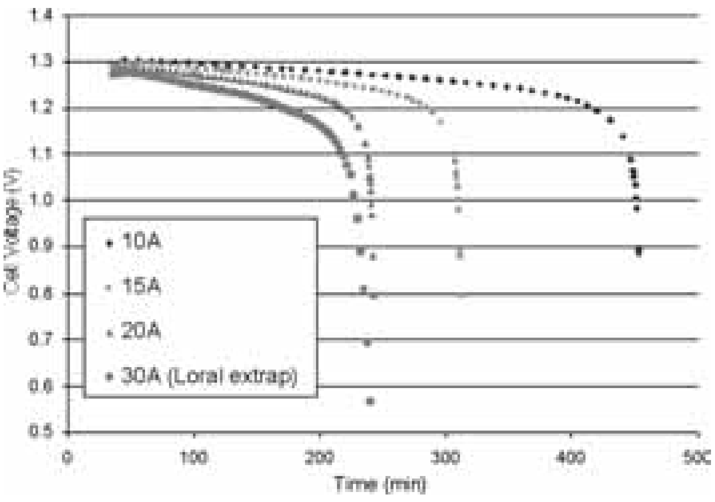


Figure 10. Example of Space Systems Loral current extrapolation.

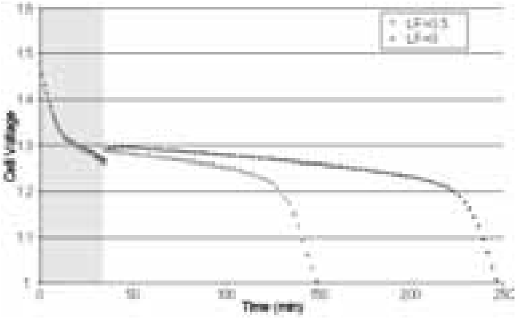


Figure 11. Example output for two different life fractions at 40A, 28.81% DOD and 0°C.

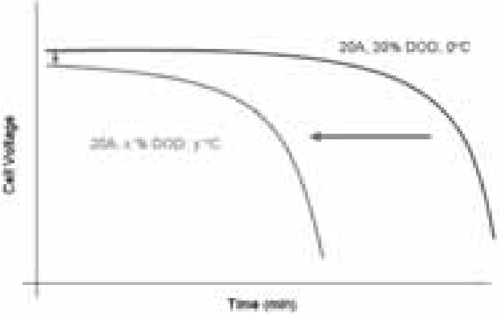


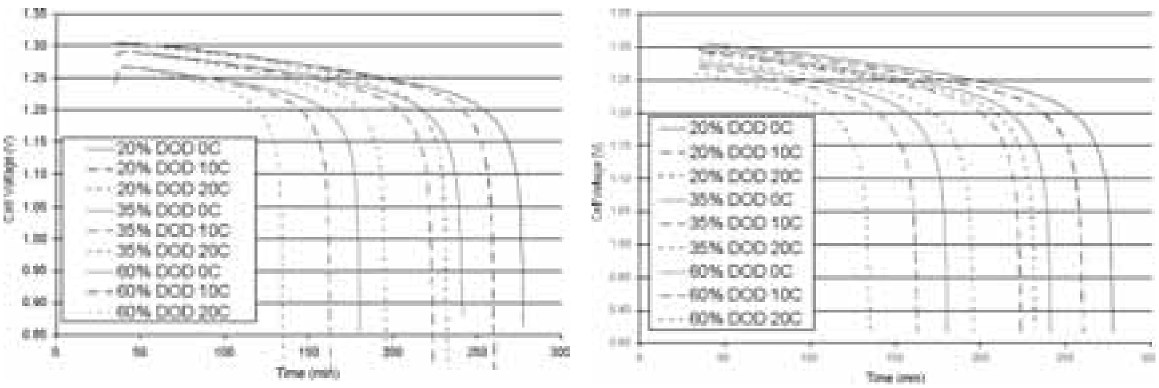
Figure 12. Combined Shift Methodology

Combined Shifting

Combined Shifting Methodology

In Figures 5 and 6, it can be seen that the baseline extended discharge curves all look similar. In the previous section, it was shown that the curves can be described by similar forms of regression lines. Two different curve regressions generally only differ by *Tend* and V_{adj}.

The idea behind the combined shifting method is simple. Since all of the extended battery discharge voltage



a) Space Systems Loral baseline curves at 20A.

b) Derived curves from shifting 20% DOD 10A 0ºC curve.

Figure 13. Space Systems Loral baseline curves and derived curves.

curves have the same shape, the curves can be represented by one curve that is shifted horizontally and vertically, as shown in Figure 12. The time offset (horizontal) shift is dependent on the life fraction, DOD, current, and temperature. The voltage offset (vertical shift) adjusts for the initial voltage in the extended discharge phase, given the ending voltage and current of the previous discharge curve. The method for calculating this vertical shift is the same as that used in the Space Systems Loral battery model, described in section C.

The offset time due to DOD is calculated by Equation 4, which corresponds to the offset times derived from matching the Space Systems Loral baseline curves at different DODs, (see Figures 7 and 8) as shown in Table 2. The offset time due to temperature is derived from matching the Space Systems Loral baseline curves at different temperatures, producing the values in Table 3. The polynomial regression of the values in Table 3, as shown in Equation 5, provides the calculations for determining the offset time for all temperatures. The offset times for the combination of DODs and temperatures is the sum of the offset times of the individual DODs and temperatures.

$$Toffset_{DOD} = (DOD - 20\%) \cdot 81Ahr \cdot \frac{60^{\min}/hr}{20A} \quad (4)$$

Table 2: Time offsets varying with DOD

	20% DOD	35% DOD	60% DOD
Time Offset (min)	0	36.45	97.20

$$Toffset_{Temp} = 0.0525(Temp)^2 + 1.221(Temp) \quad (5)$$

$$Toffset_{Total} = Toffset_{Temp} + Toffset_{DOD} \quad (6)$$

Table 3: Time offsets varying with temperature

	0ºC	10ºC	20ºC
Time Offset (min)	0	17.46	45.42

The enhancement to SPACE now performs a linear interpolation using the three values shown in Table 3. A linear interpolation using Equation 5 can also be performed.

Since the baseline curve at 20% DOD, 10A and 0°C is the longest baseline curve, it is used as the curve from which all the other curves are derived. Figure 13a and 13b compare the Space Systems Loral baseline curves with the same curves derived from shifting the 20% DOD 10A 0°C curve.

Validation

The two sets of curves in Figure 13 look similar, indicating that combined shifting is a reasonable method. In order to validate the new method, each Space Systems Loral curve needs to be compared with its derived counterpart and conduct a correlation comparison. Of the 27 Space Systems Loral baseline curves, the 60% DOD 20A 20°C curve is farthest away from the 20% DOD 10A 0°C baseline curve. If this curve correlates well with its derived counterpart, confidence can be gained in the validity of the combined shift model. Figure 14 compares the two models and Figure 15 conducts a correlation between them.

From Figure 15, the correlation coefficient between the 60% DOD 20A 20°C Space Systems Loral baseline curve and the 60% DOD 20A 20°C curve derived from shifting the 20% DOD 10A 0°C curve is 0.9564. The correlation is high enough to validate the similarity between the two models.

One thing to note is that by shifting the 20% DOD 10A 0°C curve to create the other desired curves, the voltages near the knee of the curve are always underestimated, as can be seen in Figure 14. This is due to the smaller rate in voltage drop in the 20% DOD 10A 0°C curve, and is acceptable for two reasons: first, underestimating the voltage produces a conservative model. In other words, it is acceptable for the model to predict a slightly lower voltage rather than a slightly higher voltage because this is a more conservative result. Second, since the purpose of the extended battery discharge model is to predict when the battery cell voltage will be too low, obtaining the correct time when the cell voltage reaches 1 volt is more important than the actual shape of the voltage curve. Therefore, to sum up, the enhancement to SPACE contains a simplified extended battery discharge curve that matches the Space Systems Loral battery performance model with an accuracy of over 95%, and with the error being conservative. Furthermore, the model is designed to match the time to reach one volt, and thus accurately captures the most important piece of information on the extended discharge curve.

Future work and other considerations

Although there is currently an abundance of regular battery cycling data from both on-orbit operations and ground tests, there is little data regarding extended battery discharge as this is not a common occurrence. Even though there is little ground testing or on-orbit data for extended battery discharge, it would be useful to compare the extended battery discharge model with this limited data to validate the model predictions.

An arithmetic arc-length interpolation technique, as depicted in Figure 16, has been developed by Eric Gustafson at NASA Glenn Research Center. It is an improvement on the time-based and voltage-based methods. This technique can also be modified to become ratio arc-length interpolation. While these methods are not currently employed in extended battery discharge modeling, they may prove useful in the future.

Concluding Remarks

The existing models used to describe extended battery discharge voltage were discussed, including their capabilities and limitations. A new model called ”combined shifting” is proposed to improve the interpolation methodology and be incorporated into SPACE. The reasoning behind this model is described, and it is shown that the worst case correlation coefficient with the Space Systems Loral baseline curves is over 95%.

Acknowledgements

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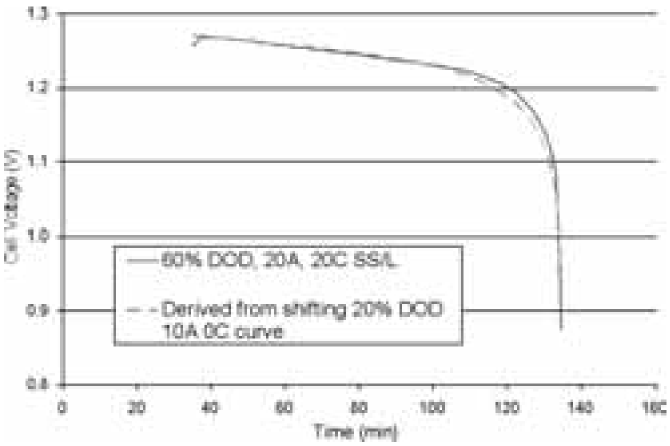

Figure 14. Space Systems Loral baseline curve and derived curve at 60% DOD, 20A and 20ºC.

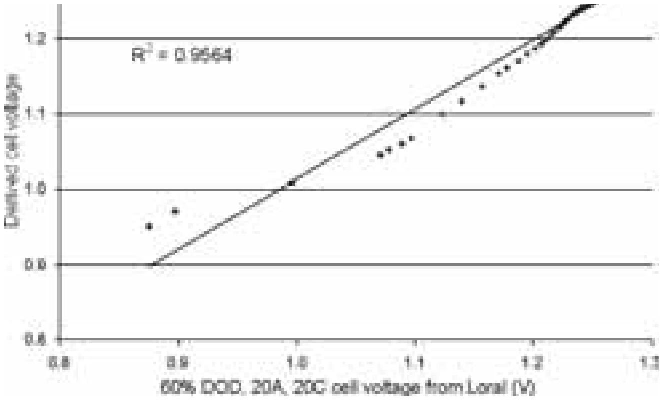

Figure 15. Correlation between Space Systems Loral and derived curves at 60% DOD, 20A and 20ºC.

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