The Effect of Variable End of Charge Management on COTS Li-Ion Batteries

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- ABSL Batteries
- Purpose of Test
- Testing Procedures
- State of Charge (SOC) Analysis Method
- Reduced End of Charge Voltage (REOCV) Results
- Conclusions
- Recommendations

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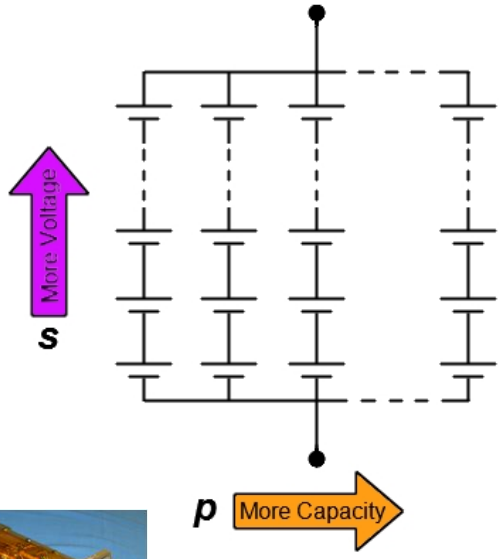
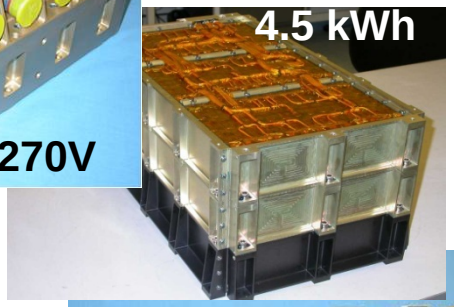
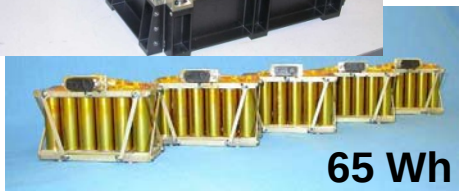
ABSL Batteries

- **The s-p topology**
  - S = number of cells in series ; principally determines battery voltage.
  - P = number of strings in parallel; principally determines battery capacity.
- **Highly Flexible**: same architecture can support a variety of battery capacities and voltages
- **Completely Passive**: no external electronics necessary
- **Extensive Heritage:** 31 vehicles launched with ABSL batteries; over 6,000 cell years in space w/o failure.







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Purpose of Test

- Intended to create an empirical model for Li-Ion performance prediction
- Tests designed and commissioned by NASA Glenn Research Center, performed by Crane.
- **Real Time LEO Cycling:** Varied EOCVs, DODs and temperatures from multiple manufactures.
  - 10 ABSL 4s4p modules, employing the ABSL 18650HC cell

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Purpose of Test

- **Value to ABSL:** Assess the effects of reduced end of charge voltage (REOCV) on life.
  - It appears that REOCVs could reduce fade based on witnessed storage data.
  - ABSL has extensive life test data at 4.2V EOC, but little at lower EOCVs.

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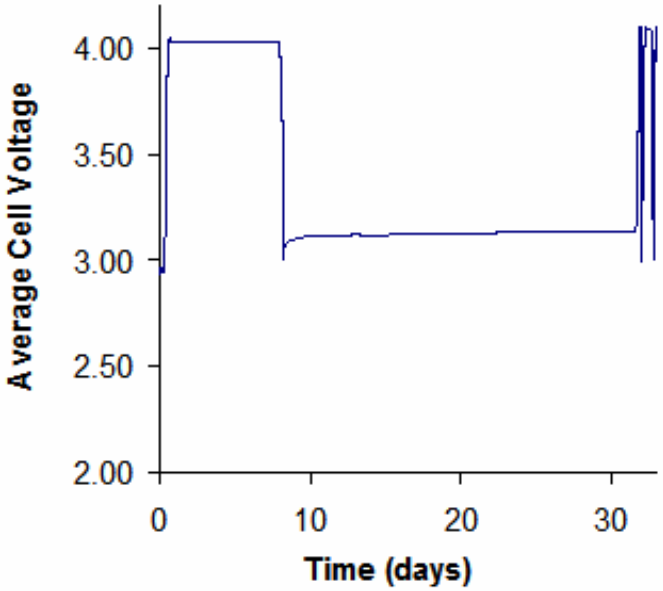
Testing Procedures

- **Pre-Cycling Procedures**:
  - Open Circuit Voltage Decay
    - 1 week at 4.1V/cell
  - Capacity Measurement
    - C/2 discharge to 3.0V/cell
    - C/5 charge to 4.1V/cell, taper charge to C/50
    - Approximately 4 cycles per module



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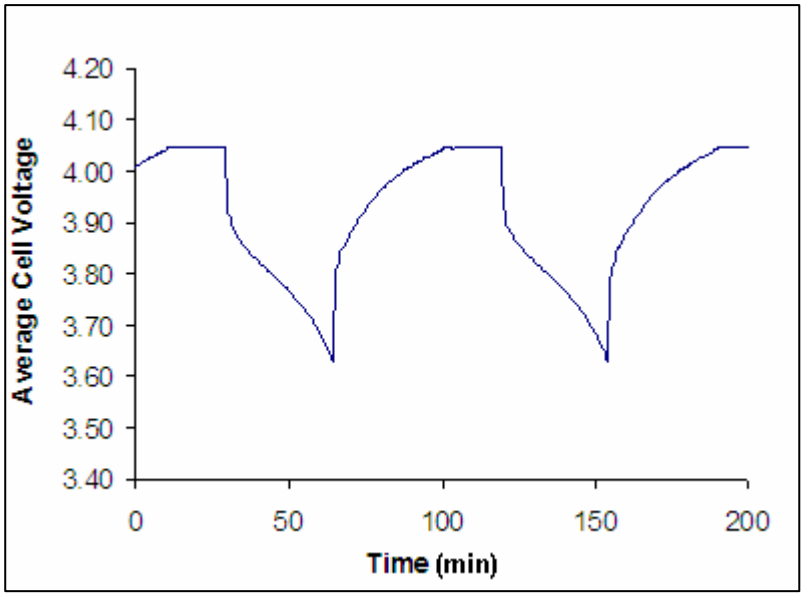
Testing Procedures

- **Cycling Procedures**:
  - Discharge for 35 minutes, rate based on desired DOD and measured capacity.
  - Charge for 55 minutes, rate selected to replace 110% of removed capacity.



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Testing Procedures

- **Operational Capacity Measurements**
  - Every 1,000 cycles
  - Temperature, rates, and EOCV unchanged from cycling
  - EODV reduced to 3.0V/cell

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Testing Procedures

- Cycling Conditions

Cell EOCV (V)	Temperature (°C)	DOD (%)	Charge Rate (C)	Discharge Rate (C)
4.05	30	20	0.17	0.25
4.05	10	30	0.26	0.37
4.05	20	40	0.35	0.49
4.05	10	40	0.35	0.49
3.95	20	20	0.17	0.25
3.95	30	30	0.26	0.37
3.85	10	20	0.17	0.25
3.85	30	20	0.17	0.25
3.85	20	30	0.26	0.37
3.85	30	40	0.35	0.49

More than 7,000 cycles and counting…

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SOC Analysis Method

- Need to compare capacity fade between varied EOC and DOD cases, but this is not straightforward…
  - Few operational capacity measurements available with different conditions between cases.
  - Can't directly compare EODV's because of different EOCV's, DOD's, rates, and temperatures.
  - Therefore, a method to calculate total capacity independent of cycling conditions has been derived.

Calculate EMF @ EOD, EOC

Calculate ΔSOC from EOC to EOD

Use change in ΔSOC over time to calculate fade

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SOC Analysis Method

- First, calculate effective cell resistance @ EOD.

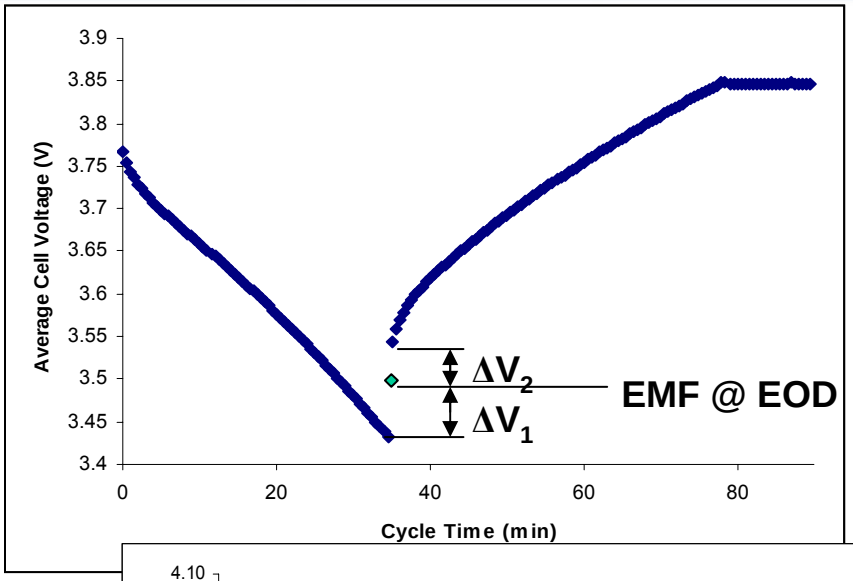
$$\Delta V_1 = -R_{EOD} I_{EOD}$$
$$\Delta V_2 = R_{EOD} I_{BOC}$$
$$R_{EOD} = (\Delta V_1 + \Delta V_2) / (I_{BOC} - I_{EOD})$$

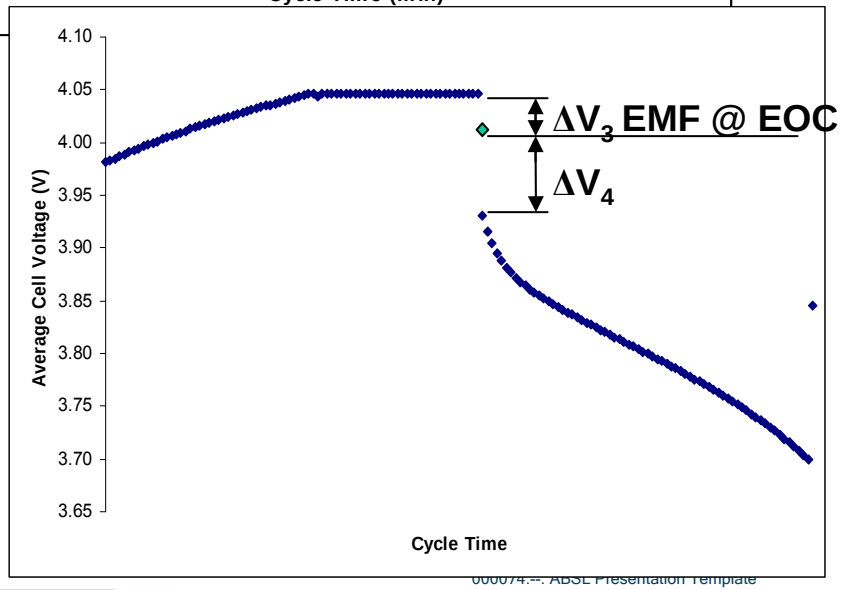
- Next, calculate EMF @ EOD

$$EMF_{EOD} = V_{EOD} - I_{EOD} R_{EOD}$$

- Then calculate EMF @ EOC via a similar process…

$$R_{EOD} = (\Delta V_3 + \Delta V_4) / (I_{EOC} - I_{BOD})$$
$$EMF_{EOC} = V_{EOC} - I_{EOC} R_{EOC}$$





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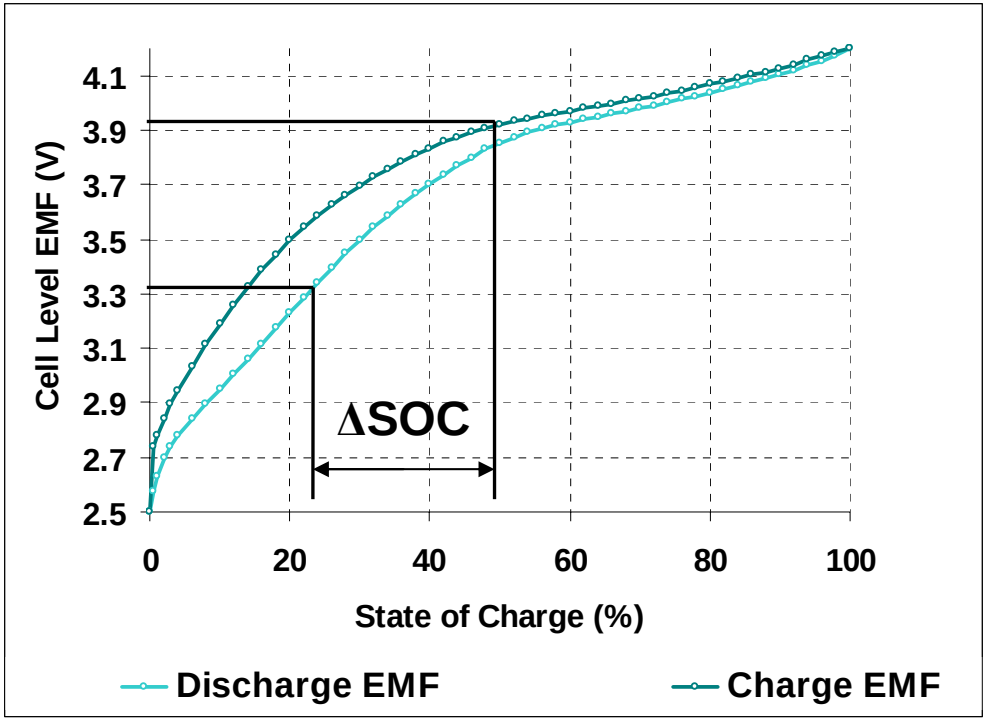
SOC Analysis Method

- Calculate change in state of charge (ΔSOC) for each discharge.
- Calculate percent retained capacity by dividing the change in state of charge of the first discharge (ΔSOC(1)) by the ΔSOC(N) of any later discharge.
  - EMF vs. SOC plot must be known over life.



Retained Capacity (*N*) = 100% x ΔSOC (*1*) / ΔSOC (*N*)

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  - *Module 7 & EOCV Scheduling:* A Model for Future On-Orbit Operations
  - *Case Study:* Extending Mission Life
  - *Comparison with ABSL REOCV data:* Accuracy of the SOC Analysis Method
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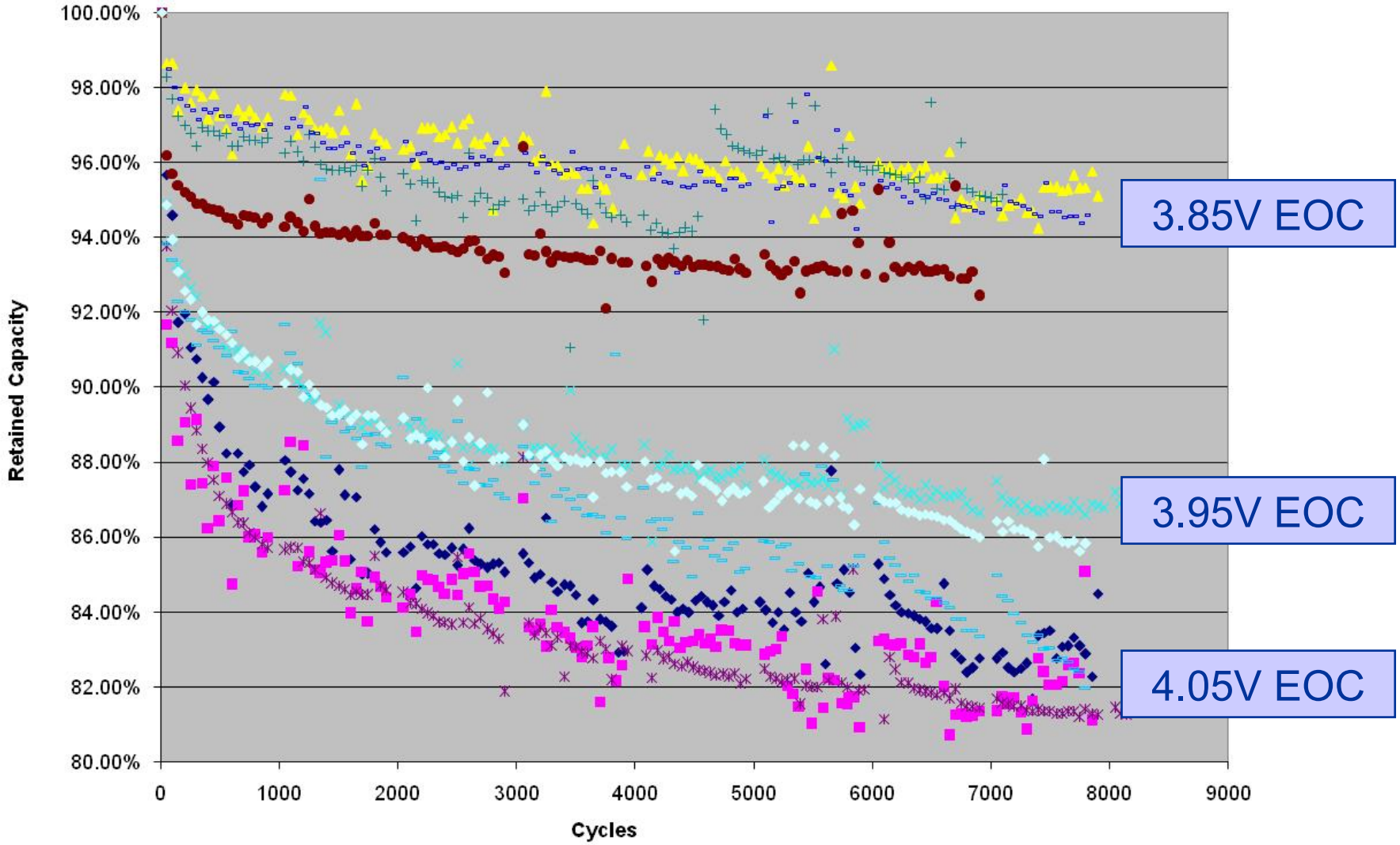
Retained Capacity for All Cases



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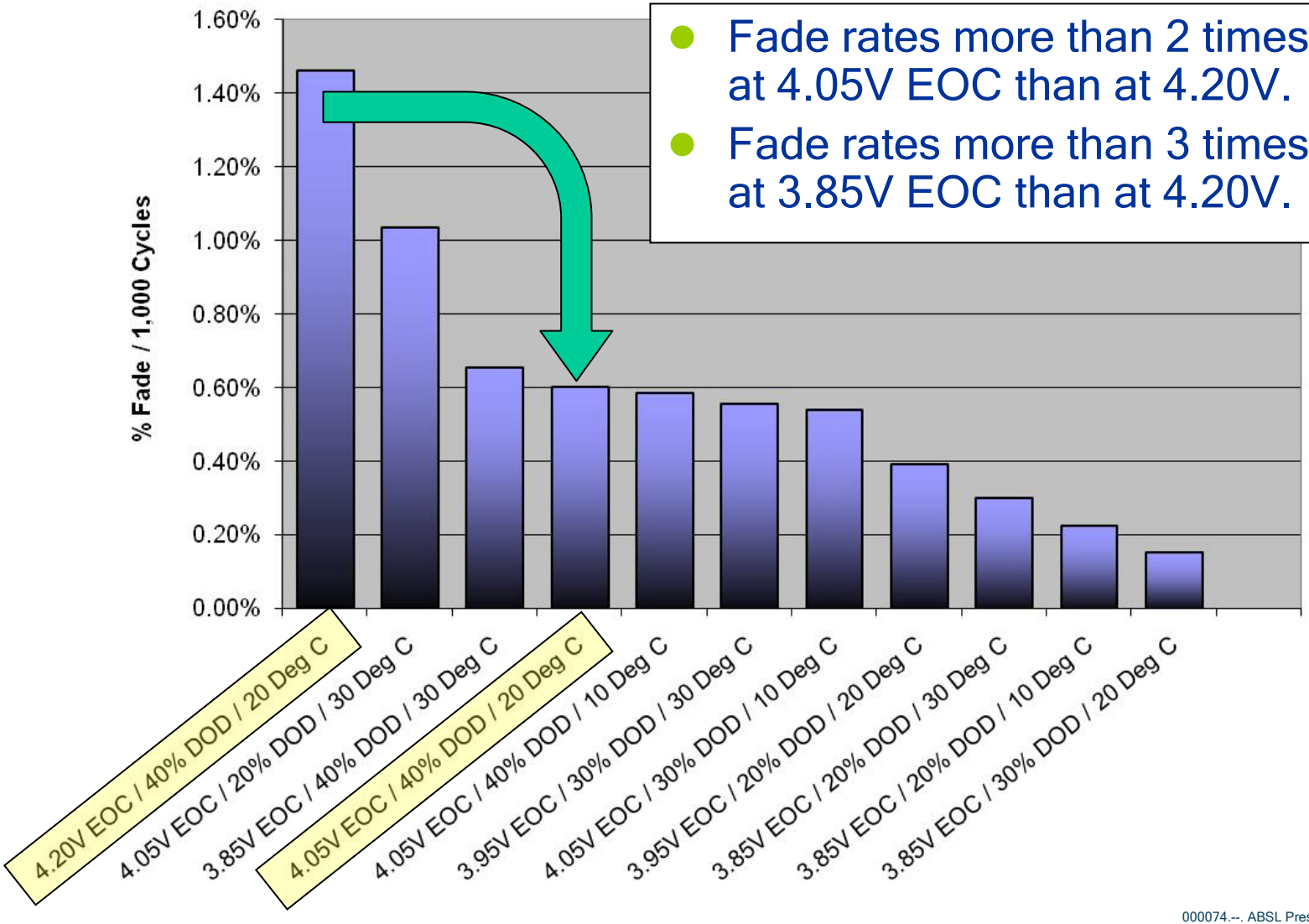
Steady State Fade Rates



- Fade rates more than 2 times slower at 4.05V EOC than at 4.20V.
- Fade rates more than 3 times slower at 3.85V EOC than at 4.20V.

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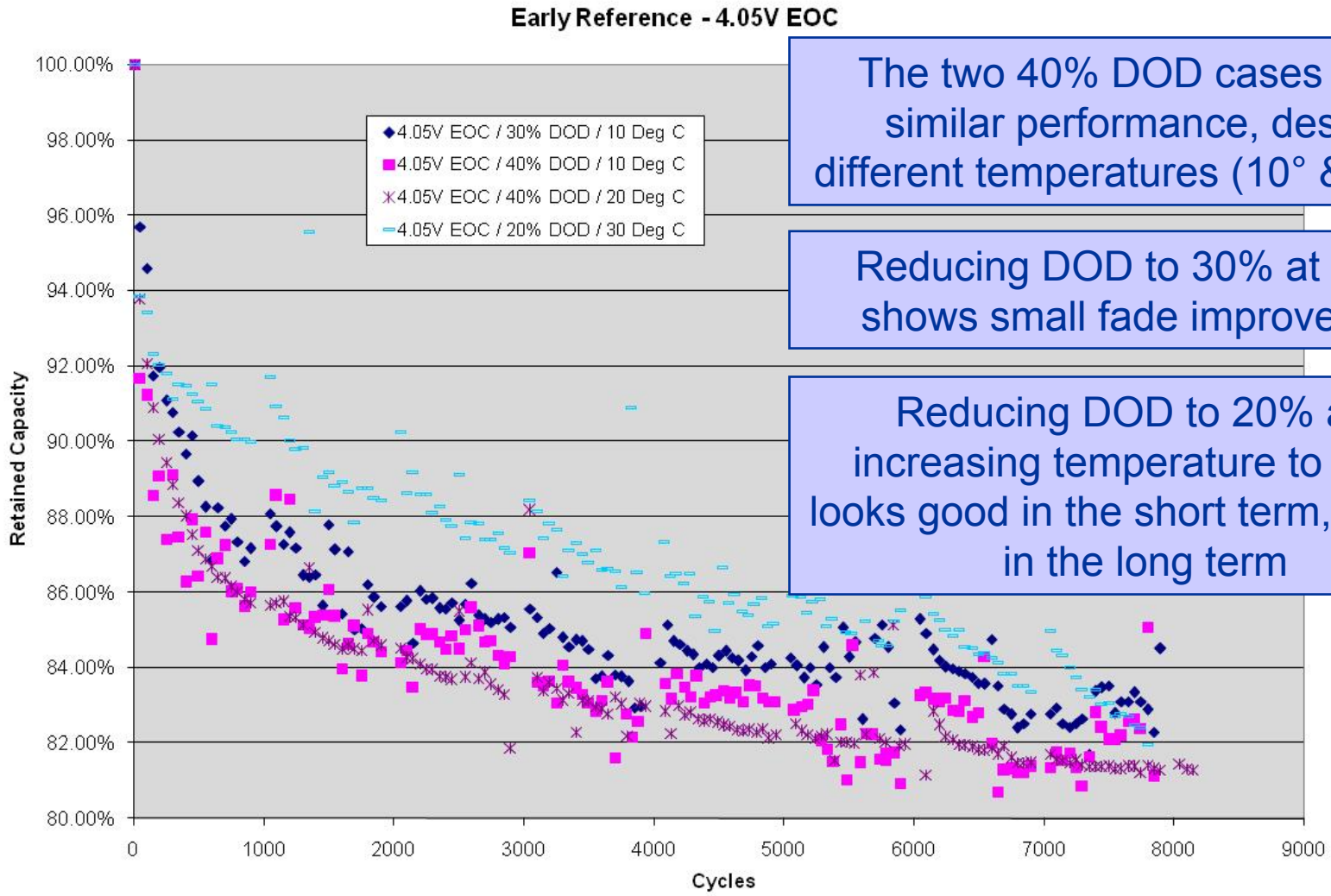
4.05V EOC Retained Capacity



The two 40% DOD cases show similar performance, despite different temperatures (10° & 20° C)

Reducing DOD to 30% at 10° C shows small fade improvement

Reducing DOD to 20% and increasing temperature to 30° C looks good in the short term, but bad in the long term

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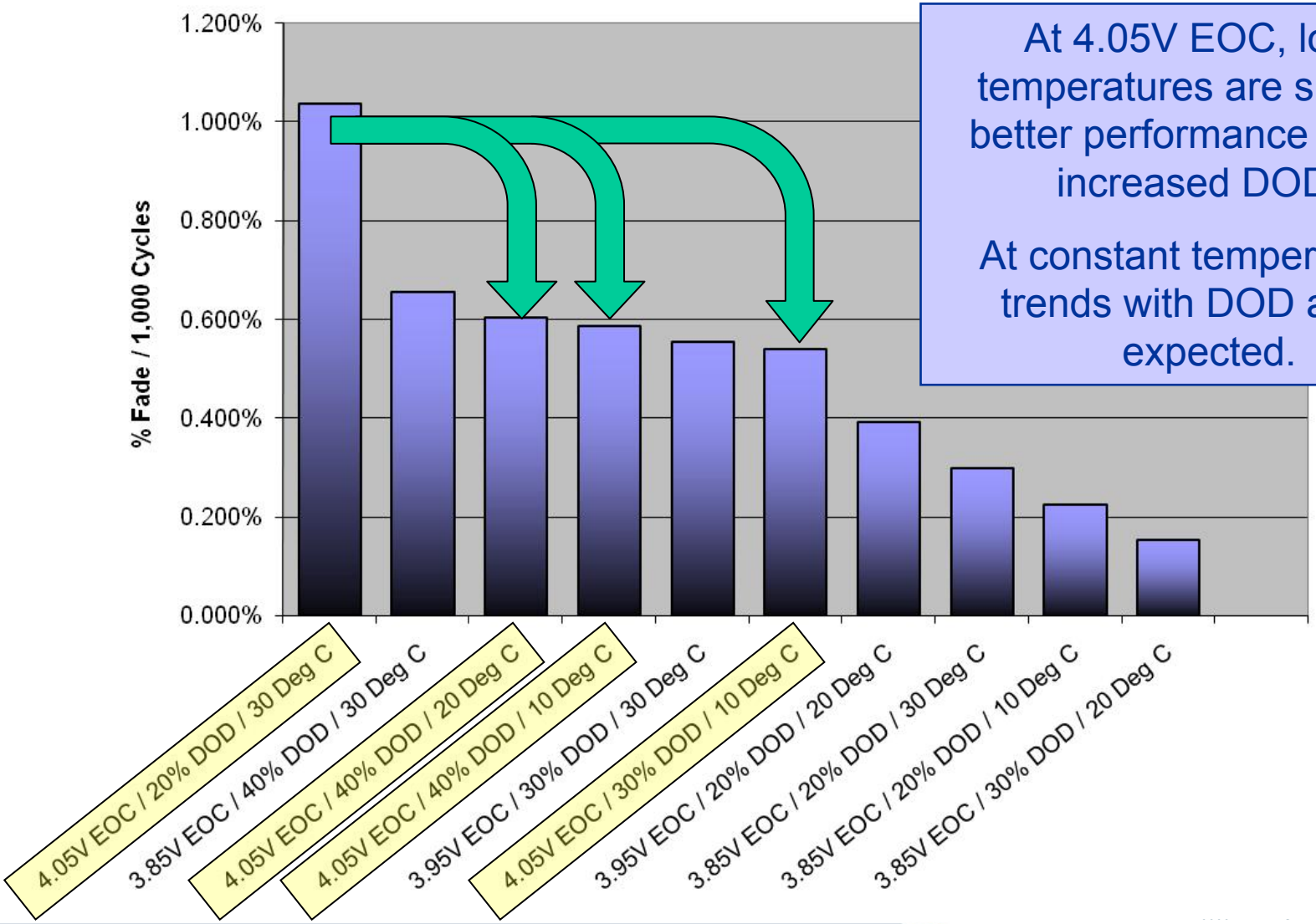
Steady State Fade Rates



At 4.05V EOC, lower temperatures are showing better performance despite increased DODs.

At constant temperatures, trends with DOD are as expected.

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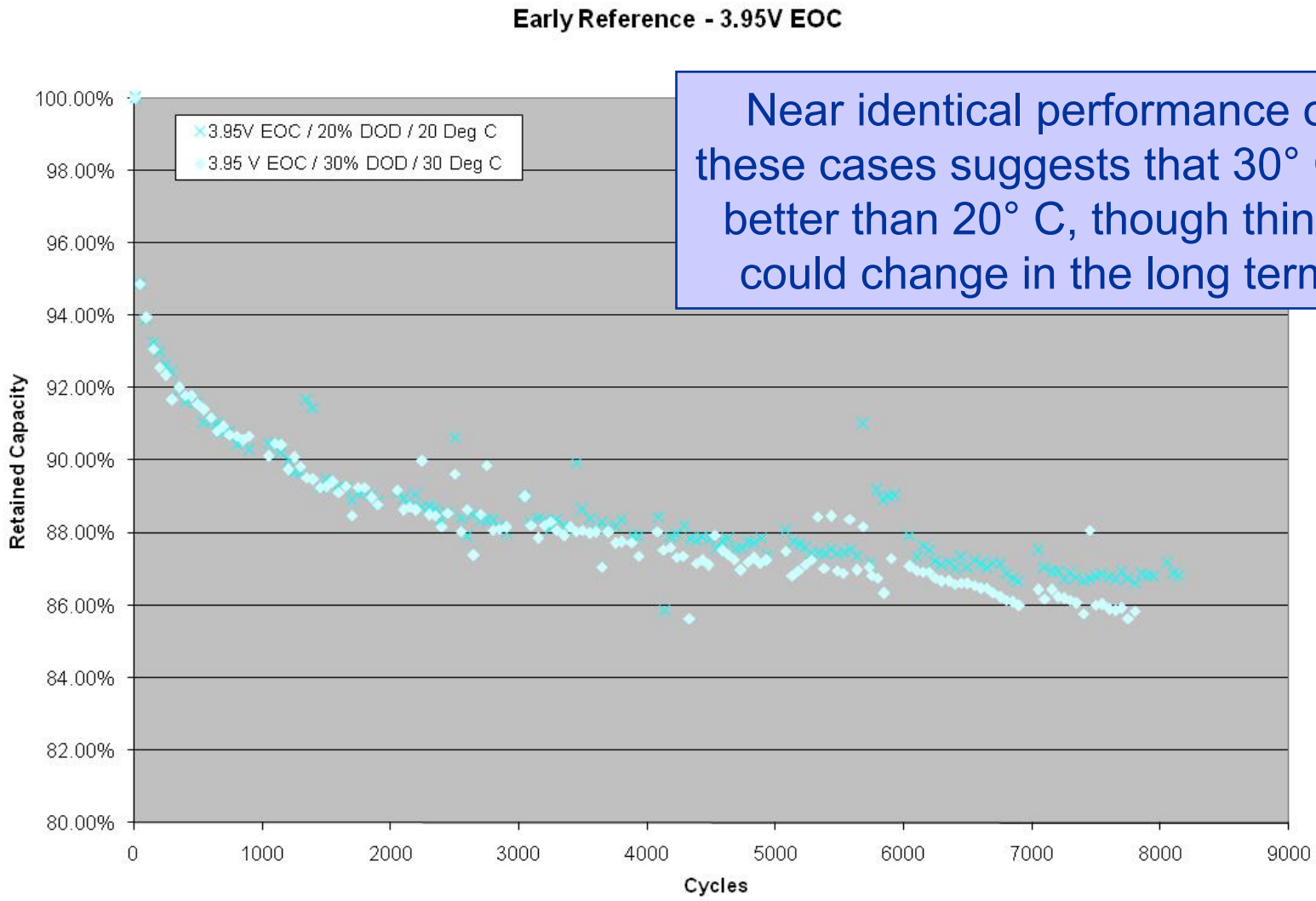
3.95V EOC Retained Capacity



Near identical performance of these cases suggests that 30° C is better than 20° C, though things could change in the long term.

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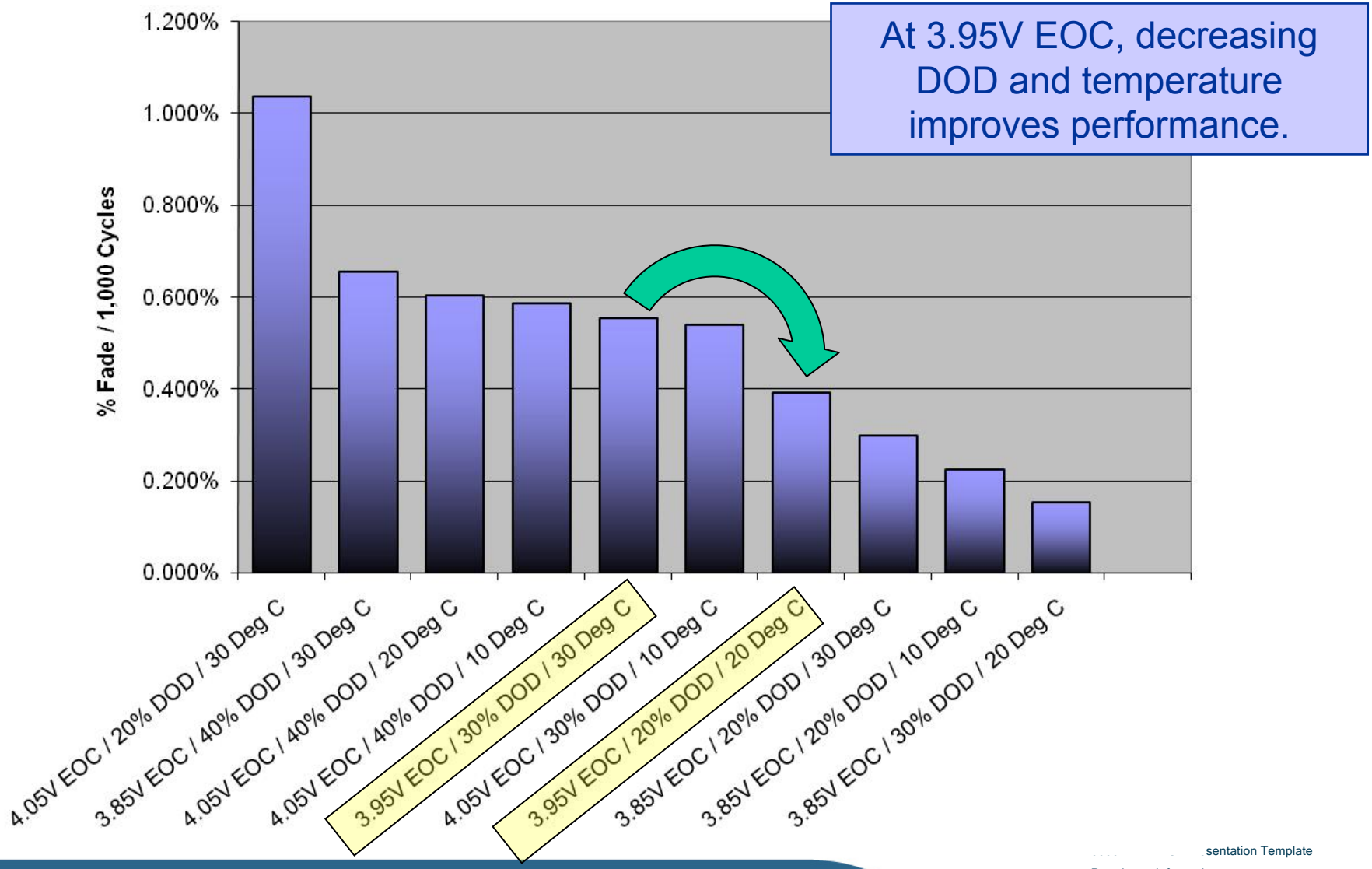
Steady State Fade Rates



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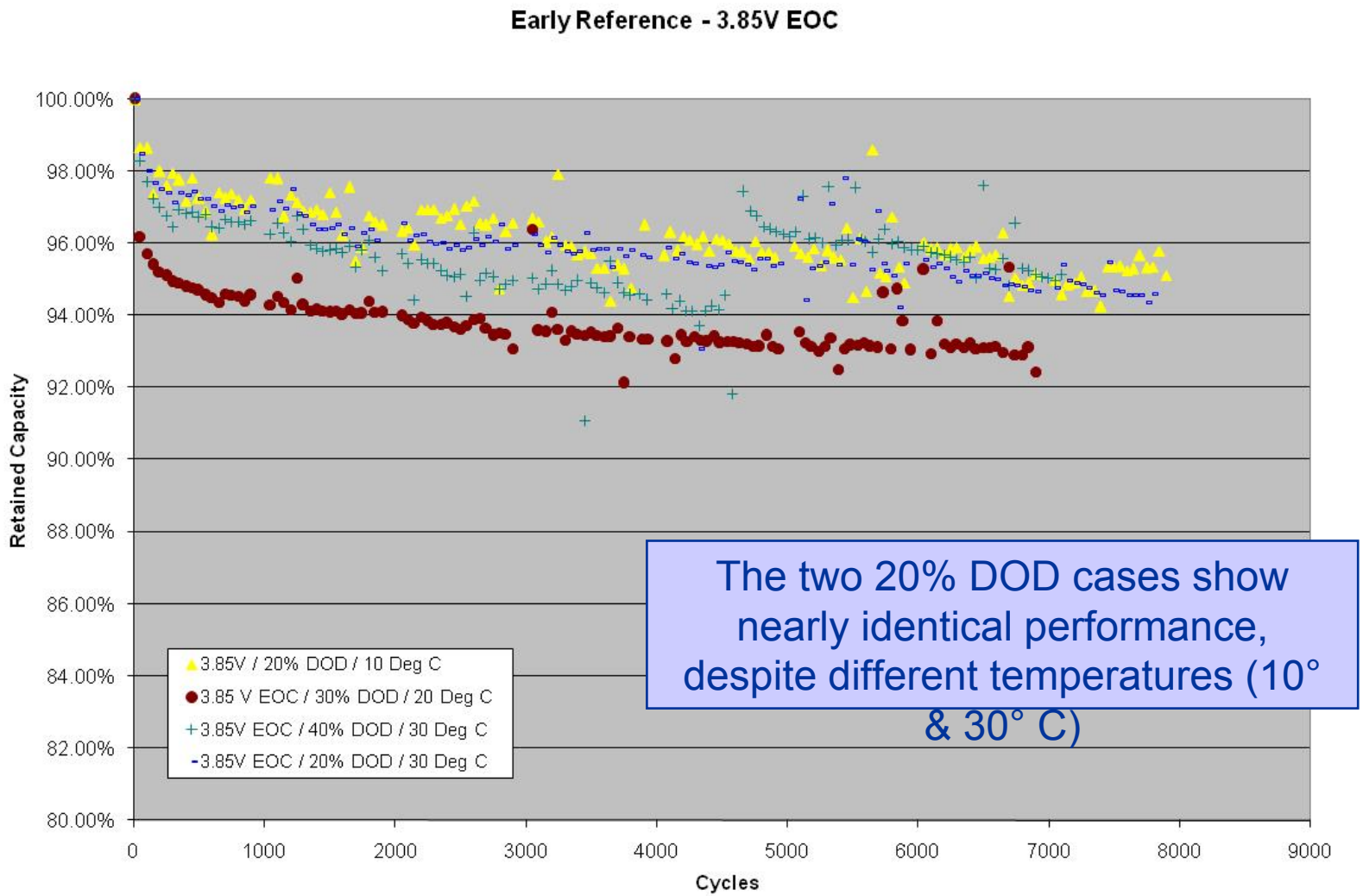
3.85V EOC Retained Capacity



The two 20% DOD cases show nearly identical performance, despite different temperatures (10° & 30° C)

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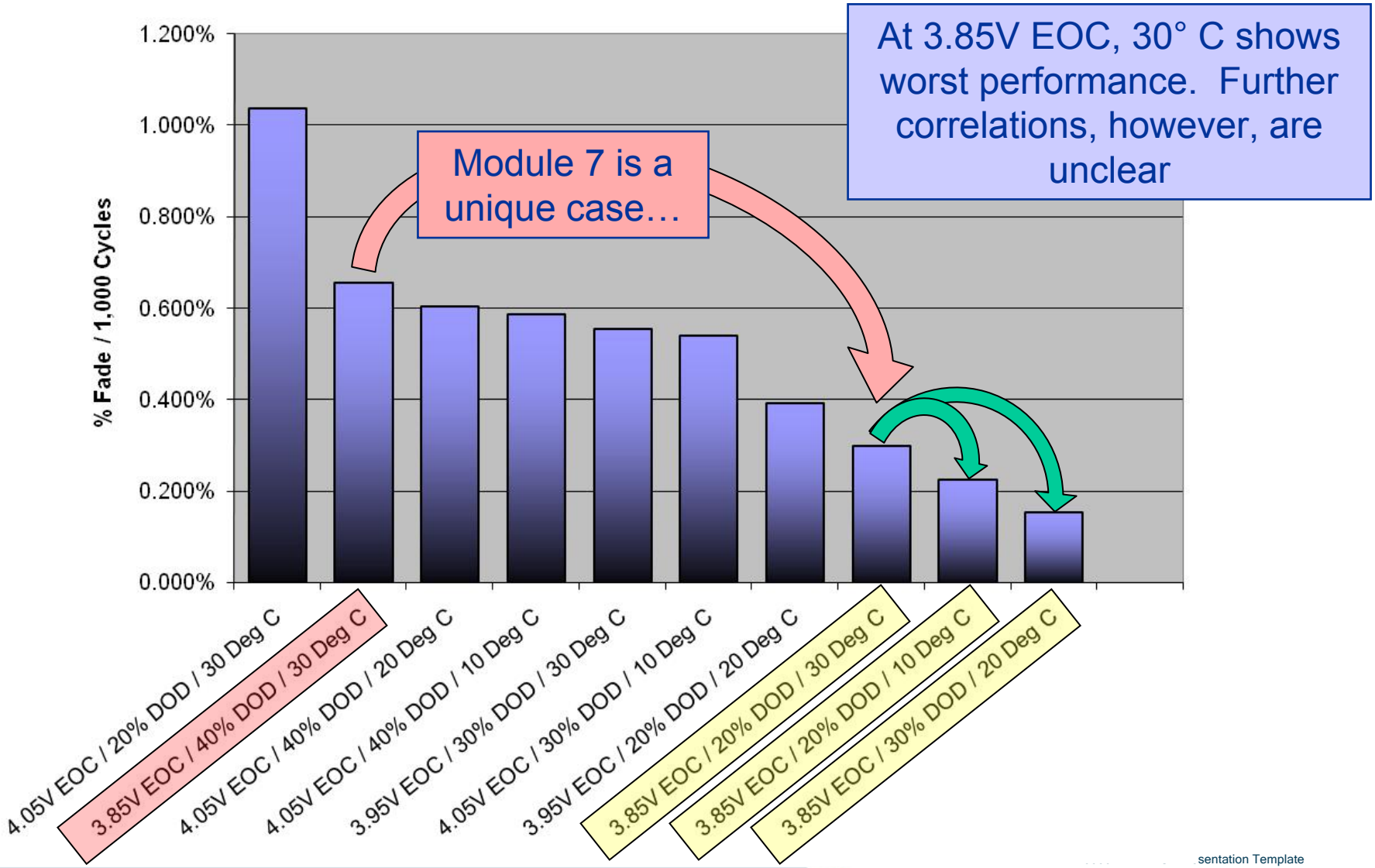
Steady State Fade Rates



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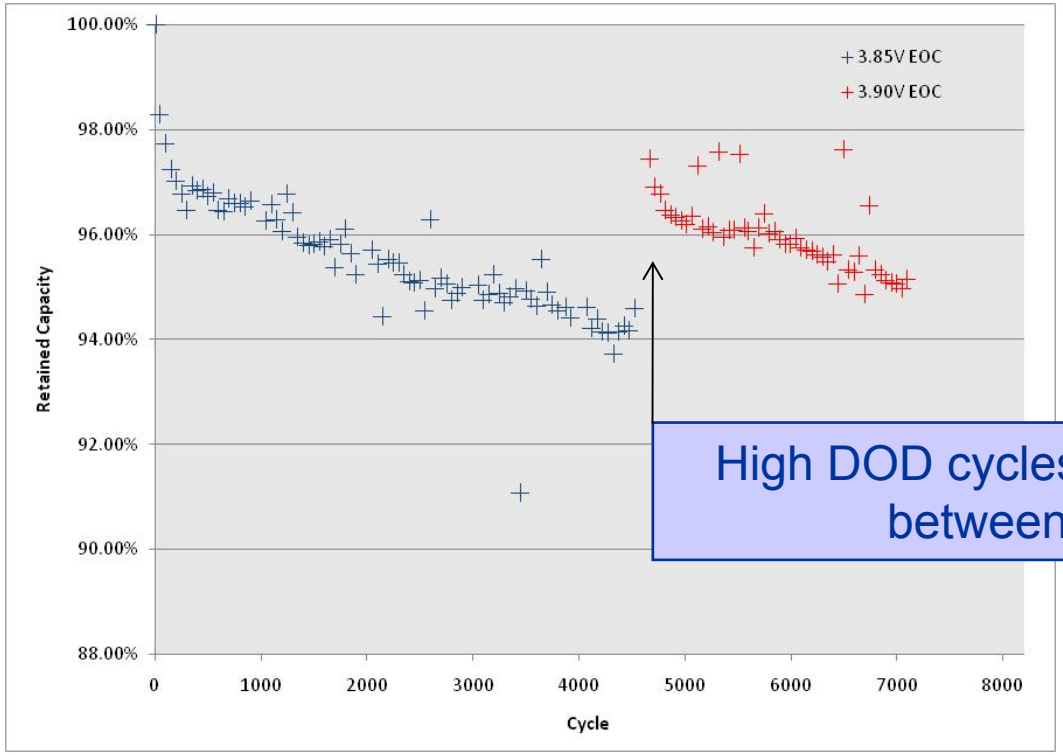
Module 7 & EOCV Scheduling

- EOCV Scheduling Example
- Module 7: 3.85V EOC, 40% DOD, 30° C
  - Reached 3.0V/cell at EOD
  - EOCV increased to 3.90V/cell to compensate



High DOD cycles and rest period between EOCVs

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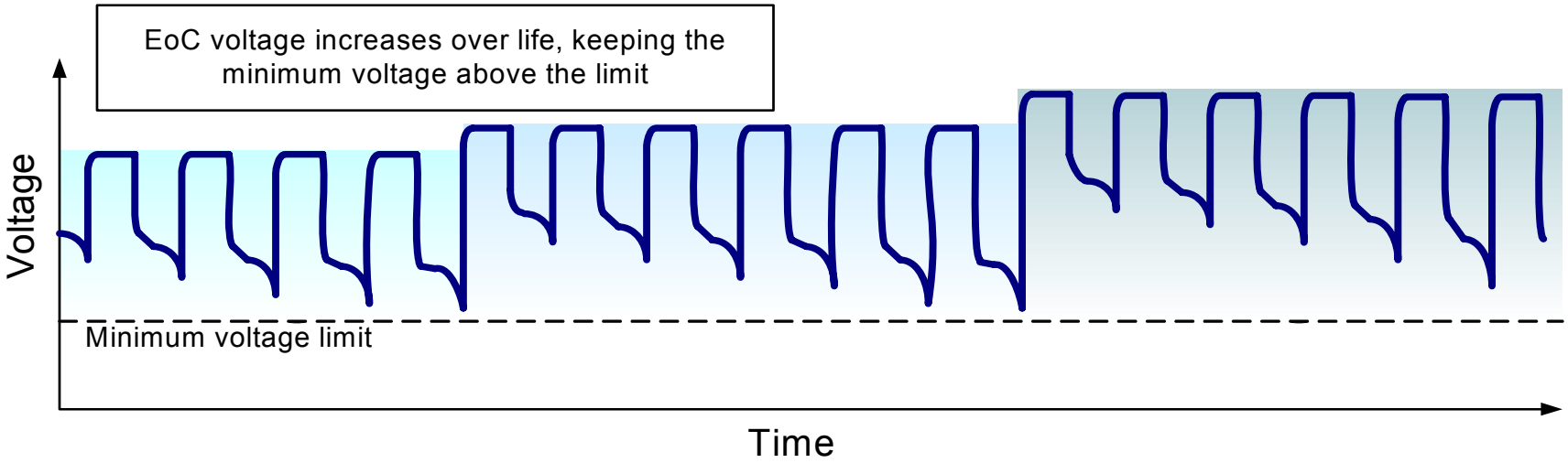
Module 7 & EOCV Scheduling

- EOCV Scheduling
  - Long term performance improves at lower EOCVs…
  - …But lower EOCVs mean the min EODV will be met sooner
  - Therefore, the envisioned method of operation is EOCV scheduling, where the user raises the EOCV each time the EOD cutoff voltage is met.



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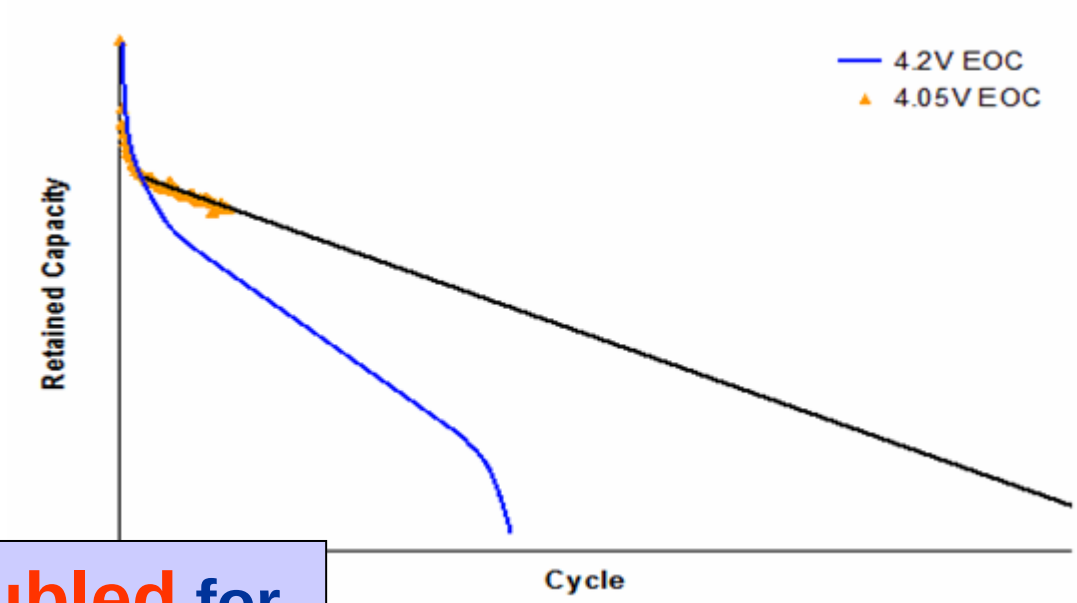
Case Study

- 4.2V EOCV life test data shows three regions.
- Batteries typically sized to operate to the end of region 2.
- Assuming…
  - End of region 2 is at the same retained capacity
  - Region 2 fade rate stays linear



Lifetime could be doubled for 40% DOD missions by reducing EOCV from 4.2V to 4.05V

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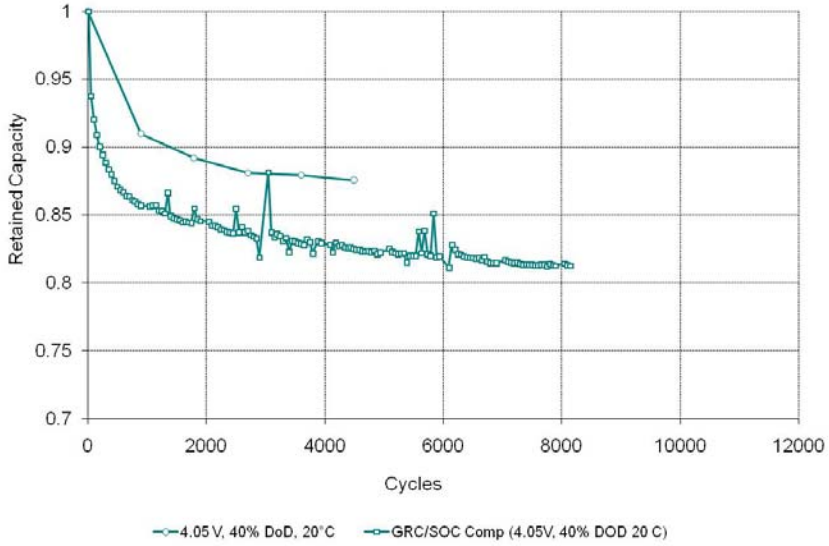
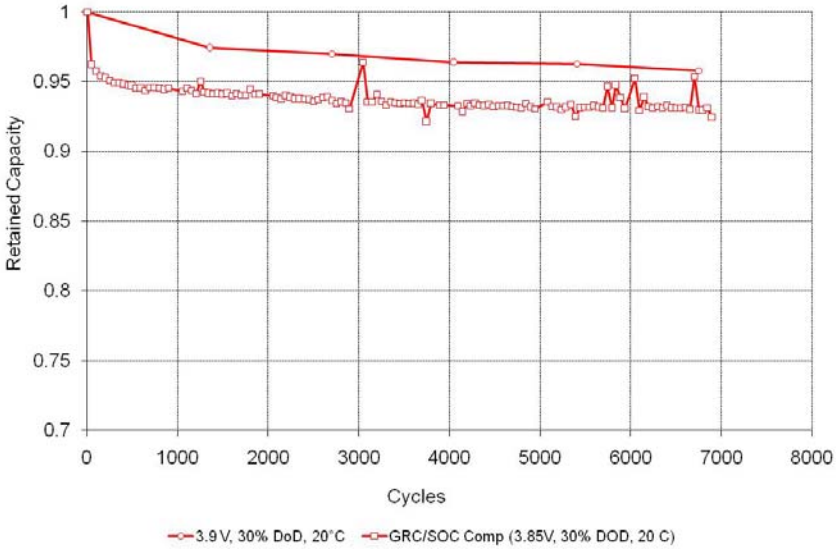
Accuracy of the SOC Analysis Method

- Witnessed error between ABSL's lifetesting with SCMs and the GRC data analyzed with the SOC method is 3 to 6%.
- Offset is conservative and largely constant – thus steady state fade rate predictions are expected to be very accurate.





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Results

- Capacity retention through life is strongly dependent on EOCV, improving as voltage levels are reduced.
- At ~8,000 cycles, fade rates are still improving ('leveling off')
- The data currently suggests that, in most cases, capacity retention over life improves as temperature is reduced.

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Conclusions

- Operation at reduced end of charge voltages offers a clear benefit in retained capacity in early cycling.
  - Initial non-linear fade is reduced significantly
  - On the order of half the steady-state fade rate & better
  - More data is needed to identify long term benefits, and to better identify DOD and temperature sensitivity

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Conclusions

- Given the excellent cycle life of the ABSL 18650HC cell at 4.2V EOC, REOCV techniques could support extremely long duration missions or a substantial reduction in battery sizes.
  - 70,000+ cycles and counting at 10% DOD
  - 35,000+ cycles and counting at 20% DOD
  - Contact ABSL for further information

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Recommendations

- Continue current testing
  - 8,000 cycles is a good start, but many more years of cycling are necessary.
- Commission more test cases within the current range of parameters.
  - Different combinations of DOD & temperature to better decouple the effects of these two factors.
- Commission higher DOD lifetests at reduced EOCVs
  - The 20, 30, and 40% DODs are fairly conservative
  - Higher DODs could be employed to reduce battery mass for the same lifetime, this data could better identify the magnitude of the improvement.
- ABSL will incorporate REOCV life testing as standard practice on its next-generation cells.

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NASA

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