Multiple Uses in Storage:
Results of Lithium-Ion Cells Tested under Stacked Cycling Profiles

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Outline

- Motivation
- Methodology
- Results
- Conclusions
EOL as a Function of SOC in LFP

Power cycling

Energy Shifting

Individual Application Test Protocols

**Frequency Regulation**

- Power Output
- SOC

**Load Leveling**

- Power Output
- SOC

**Figure 3. Peak Shaving (Management) Duty-Cycle Regimen.**

**Figure 4. Frequency Regulation Duty Cycle.**
Individual Application Test Protocols

Power Cycling
- Frequency Regulation
- PV Smoothing

Energy Cycling
- Load Leveling
- Peak Shaving
- PV shifting
- Arbitrage
- UPS Backup

Frequency Regulation
- Power Output
- SOC

Load Leveling
- Power Output
- SOC

Graphs showing power output and state of charge over time for both frequency regulation and load leveling.
Outline

- Motivation
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• Growing interest in using a single asset for multiple use-cases
• Choose how to allocate division of energy and power
Stacked Waveform Testing:

**Load Leveling**

**Test Cycle - SOC**

**Frequency Regulation**
Stacked Waveform Testing:

Load Leveling

Multi-application Load Profile

Frequency Regulation
Metrics

- More exhaustive set of metrics to include:
  - C rate capacity testing at 0.1C, 0.2C, 1C, 2C and 4C
  - Round trip efficiency
  - Power density at 1C, 2C, and 4C

- Set to run metrics at roughly monthly intervals

- Chose a commercial Li-ion cell
  - A123 nano-phosphate cell
Evaluation to Compare Cells

- Correlating degraded values of parameters
- Suggested equation: \( V_{CWF} = K_1 (V_{LL} \times V_{FR}) \)
  - \( V \) = degraded values
  - \( K_1 \) is the acceleration factor for degradation.
  - A factor \( K < 1 \) = degradation under combined waveforms is happening faster
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Metric: Round Trip Efficiency

- RTE went up or stayed the same
- No significant correlation found
- Combined Waveform (CWF) improved most significantly
- RTE appears to improve with time as side reactions are extinguished
**Metric: Self Discharge**

- Self Discharge improved
- No significant correlation found
- Frequency Regulation (FR) improved most significantly
- Self Discharge improves with time; as side reactions are likely extinguished
Metric: Capacity

CH Capacity (normalized)

DCH Capacity (normalized)

Decreases small for LL, and greater for FR and CWF
Metric: Power Density

Power Density @1C (normalized)

Power Density @2C (normalized)

Power Density @4C (normalized)

Decreases small for LL, and greater for FR and CWF
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Correlation of Capacity Degradation

- \( V_{\text{CWF}} = K_1 (V_{\text{LL}} \times V_{\text{FR}}) \)
Correlation of Power Degradation

- \( \text{VCWF} = K_1 (V_{LL} \times V_{FR}) \)
Follow-on testing – 1 additional year

- Limited test (x2)
- CWF : 1 cell failing
  - 1 cell excelling
- $K = 1.06$ (averaged)
- Tests ongoing

Incorporating high precision cycling periodically to help elucidate SOH and performance
Conclusions

- After 6 months of testing $K_1 = 1.02$
- Indicates that CWF not significant effect on degradation
- Cycled another +12 months to reevaluate
- $K_1 = 1.06$ after 18 month testing; 149,000 FR cycles

Suggested equation:

$$V_{CWF} = K_1 (V_{LL} \times V_{FR})$$

- $V$ = degraded values
- $K_1$ is the acceleration factor for degradation.
- A factor $K < 1$ = degradation under combined waveforms is happening faster
Conclusions

- Correlation between degradation on performance metrics between waveforms using equation $V_{CWF} = K_1 (V_{LL} \times V_{FR})$
Conclusions

- Correlation between degradation on performance metrics between waveforms using equation $V_{CWF} = K_1 (V_{LL} \times V_{FR})$
- $K_1 = 1.02$ after 6 months of testing (~50,000 10% cycles)
- $K_1 = 1.06$ after 18 months of testing (~150,000 10% cycles)
- Combined waveform shows increased degradation over singular profiles above the additive losses
- Value of combined uses must be weighted against this increased degradation