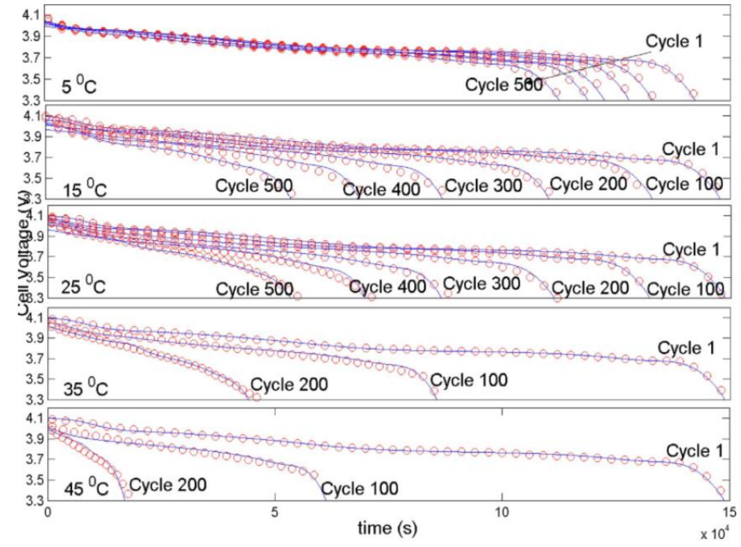
EP-C-12-014 WA 3-01

FEV Literature Review: Battery Durability in Electrified Vehicle Applications

An Overview

prepared for:

U.S. Environmental Protection Agency



Ottawa, Canada – 10/19/2015

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Summary of FEV Tasks

Task 1: Literature Review

- Existing definitions of EV battery durability
- Factors affecting EV battery durability
- Existing and emerging test programs or methodologies for evaluating EV battery durability
- Synthesis and analysis of Parts 1, 2, and 3 above including identification of gaps and/or areas of work that could be pursued by the EVE IWG.

Task 2: Additional Test Program and Methodology Recommendations

- FEV will provide additional recommendations for test programs and methodologies for evaluating EV battery durability based on FEV’s expertise on this subject

Task 3: Written Final Report

- FEV will provide a written report detailing the results and conclusions from Task 1 and Task 2

Battery Durability: Definitions & Metrics

End of Life (EOL) is typically defined as when a battery can deliver up to 80% of its rated amp-hour capacity. It is expected that by this point, the battery will still be able to meet defined performance targets.

From USABC guidelines, some of these targets are:

- Calendar Life
- Cycle Life
- Useable Energy Density @ C/3 Discharge Rate
- Peak Pulse Discharge Power
- Peak Regen Pulse Power

Battery Durability: Definitions & Metrics

Definition of xEV Battery Durability:

The ability of an electrified vehicle battery to withstand degradation of functionality such that power and energy performance targets are met during typical drive cycles, consumer usage, and storage conditions without exceeding its end-of-life cycle and calendar life specifications.

Battery Durability: Degradation Mechanisms

A variety of physical and electrochemical processes influence the longevity of lithium-ion battery cells, leading to noticeable effects such as capacity fade and power fade. These include:

- SEI Growth
- Lithium Plating
- Corrosion
- And many others…

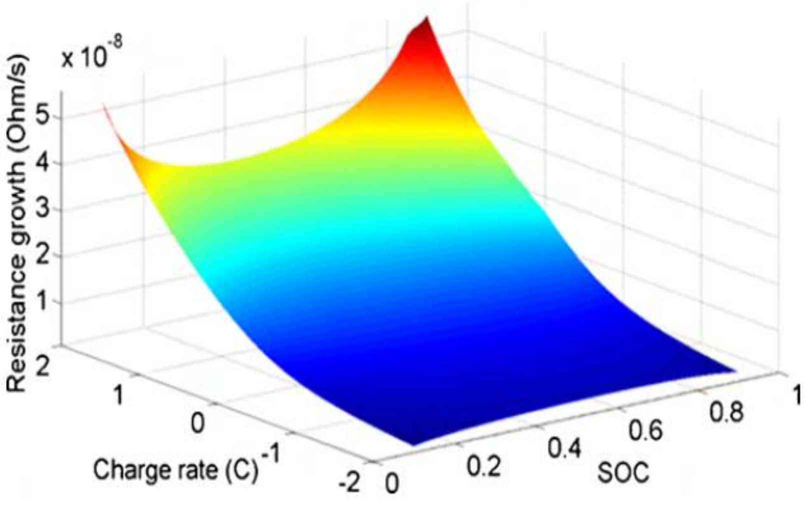
These mechanisms are described within the report to give an understanding of how macro-level stimuli (at vehicle or battery pack level) cause changes within cells which impact overall durability.

Battery Durability: Influences at Vehicle or Pack Level

FEV has focused on the following categories with respect to testing:

- **Charge Patterns and Optimization**
  - Fast charging, slow charging
  - Constant vs. variable charge patterns
- **Climate and Thermal Effects**
  - What influence does climate have on battery durability?
- **Cycling and Depth-of-Discharge**
  - Frequency of cycling
  - Depth-of -Discharge windows
- **Fleet & On-Road Testing**
  - Regular vehicle usage outside of a laboratory environment

Charging Effects: Examples

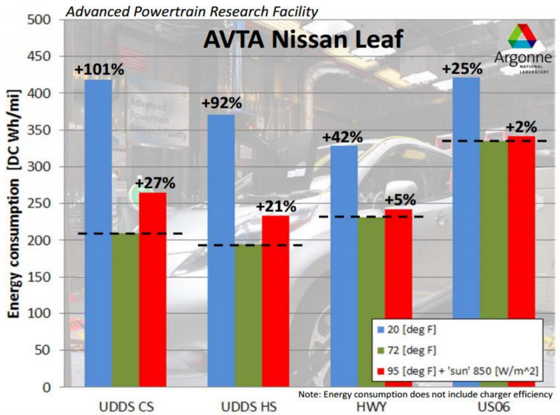


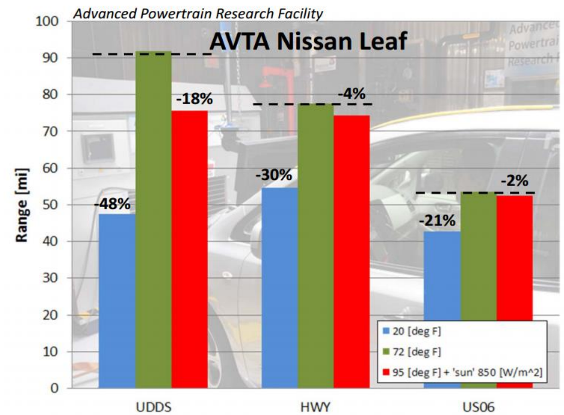
Source: S. Bashash, S. J. Moura and H. K. F. Joel C. Forman, "Plug-in hybrid electric vehicle charge pattern optimization for energy cost and battery longevity," 2010.

Battery charging pattern				Degradation	
Home charging per week		Fast charging per month		After 1000 cycles	Time (years) to 80% of new capacity
3kW	7kW	23kW	50kW		
6	0	0	0	1.5%	13.77
6	0	4	0	3.3%	6.09
6	0	0	4	5.7%	3.52
0	6	0	0	2.5%	8.01
0	6	4	0	4.3%	4.62
0	6	0	4	6.7%	2.97

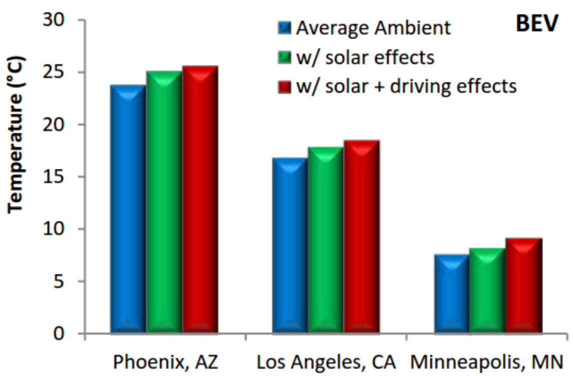
Source: G. Lacey, T. Jiang, G. Putrus and R. Kotter, "The Effect of Cycling on the State of Health of the Electric Vehicle Battery," 2013.

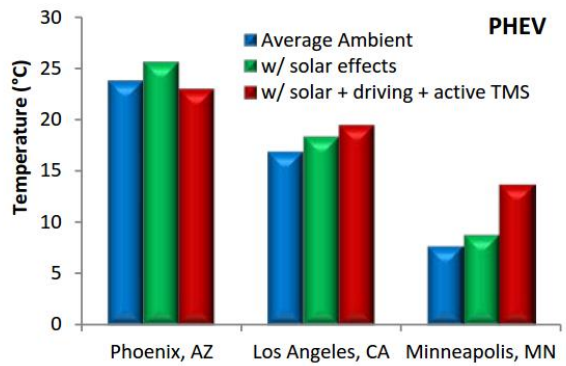
Climate and Thermal Effects: Examples





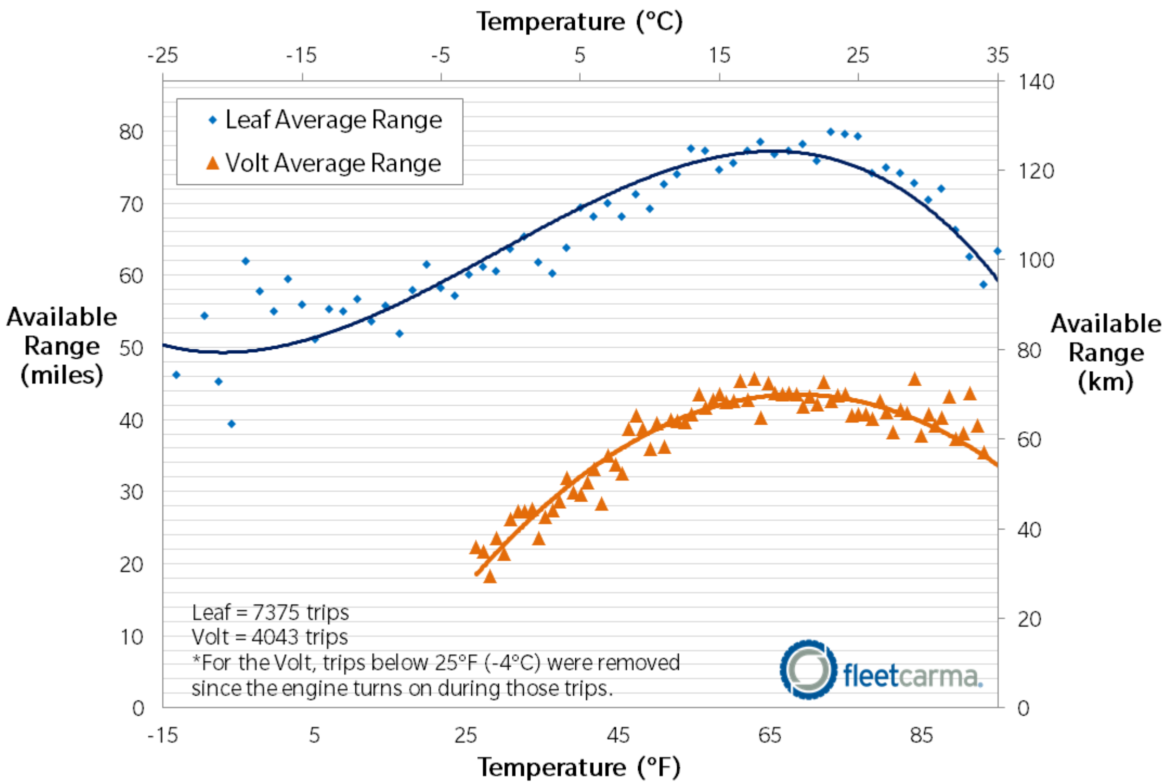
Source: H. Lohse-Busch, M. Duoba, E. Rask and M. Meyer, "Advanced Powertrain Research Facility AVTA Nissan Leaf Testing and Analysis," 2012.





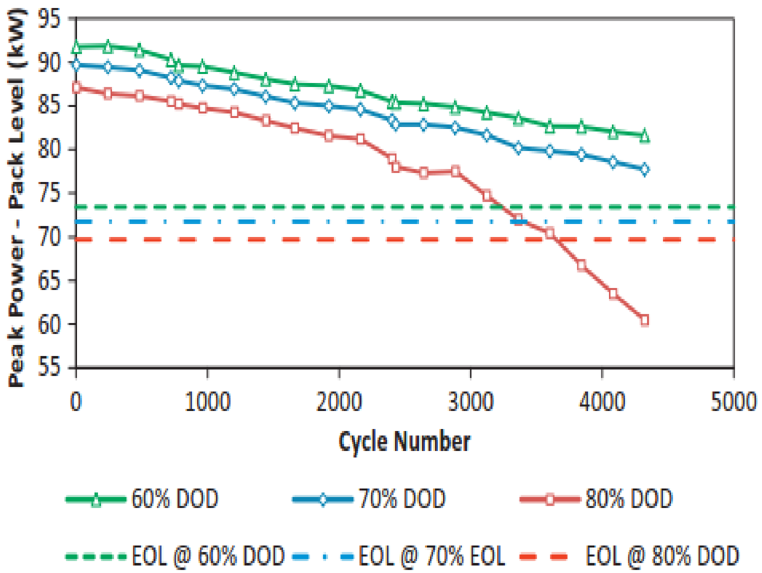
Source: E. Wood et al., "Variability of Battery Wear in Light Duty Plug-In Electric Vehicles Subject to Ambient Temperature, Battery Size, and Consumer Usage," 2012.

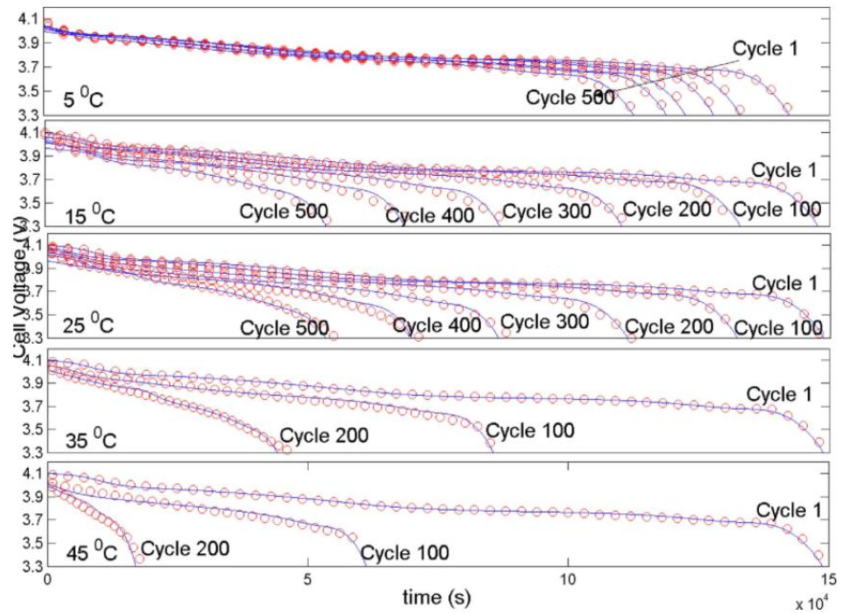
Thermal Effects: Examples



Source: M. Allen, "Electric Range for the Nissan Leaf & Chevrolet Volt in Cold Weather," fleetcarma

Cycling and Depth of Discharge Effects: Examples





Source: E. Wood, M. Alexander and T. H. Bradley, "Investigation of battery end-of-life conditions for plug-in hybrid electric vehicles," 2011.

Source: S. Santhanagopalan, Q. Zhang, K. Kumaresan and R. E. White, "Parameter Estimation and Life Modeling of Lithium-Ion Cells," 2008.

Battery Durability: Recommendations for Testing

- Systems should be tested at temperatures intended to represent hot, average, and cold climates
  - Testing should be performed using a combination of these temperatures to represent seasonal changes throughout a calendar year
  - Efforts should be made to apply climate control such that heating/cooling is provided to make the cabin temperature change to room temperature
- A combination of fast and slow charging is applied over the duration of the test
  - Ex: 80% slow charging, 20% fast charging
- Determination of drive cycles should be derived from consumer patterns
  - As the UNECE intends to use the WLTP, the constituent cycles which make up the WLTP should be applied to mimic consumer patterns
- For Calendar Life testing, worst-case combinations temperature and SOC should be considered alongside ideal cases
  - Very high or low temperatures coupled with very high or low SOC as opposed to room temperature & mid-range SOC)

Thank you for your Attention!