String Midpoint Monitoring for Li-Ion Batteries

Presented By
S. Russell, NASA Johnson Space Center

2019 NASA Aerospace Battery Workshop,
Huntsville, AL
Nov 19-21, 2019

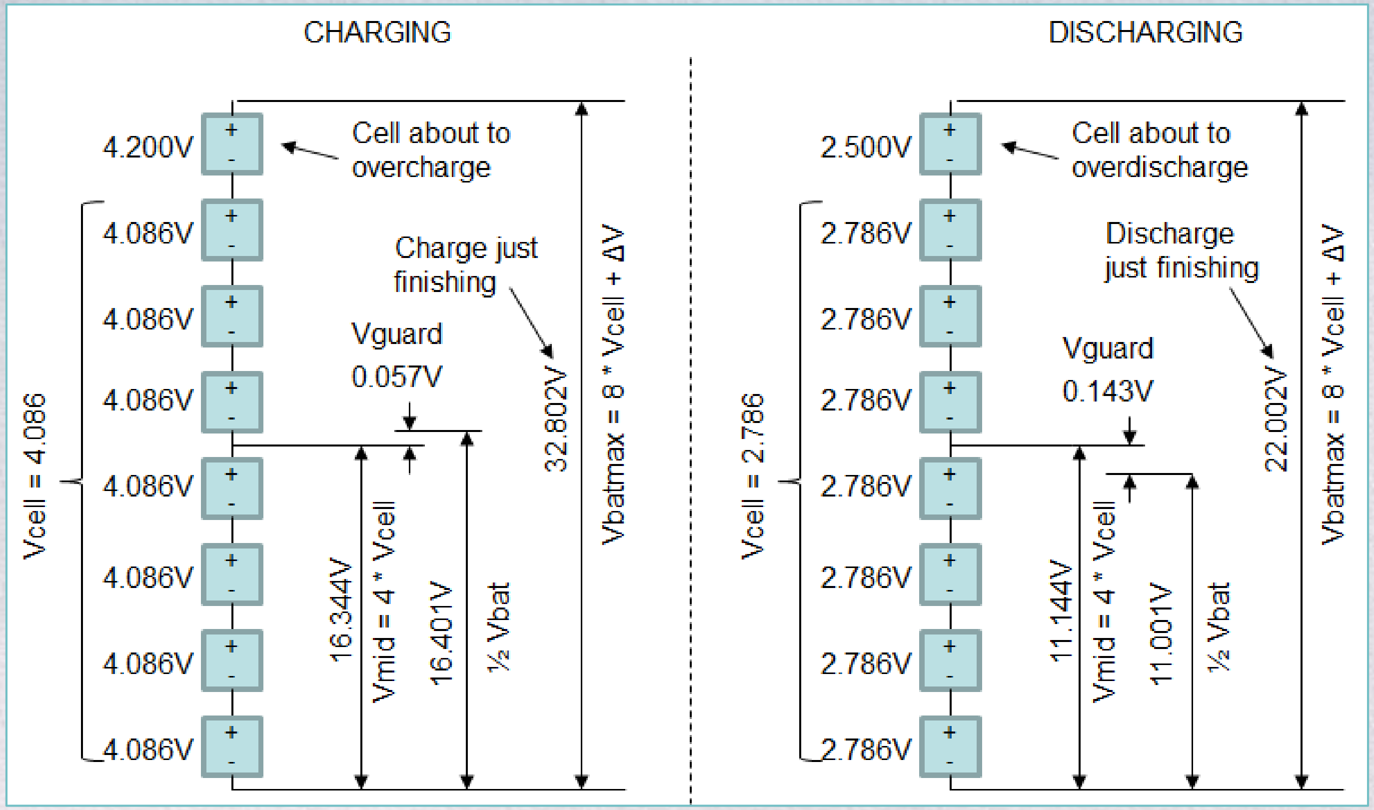
Background and Objectives

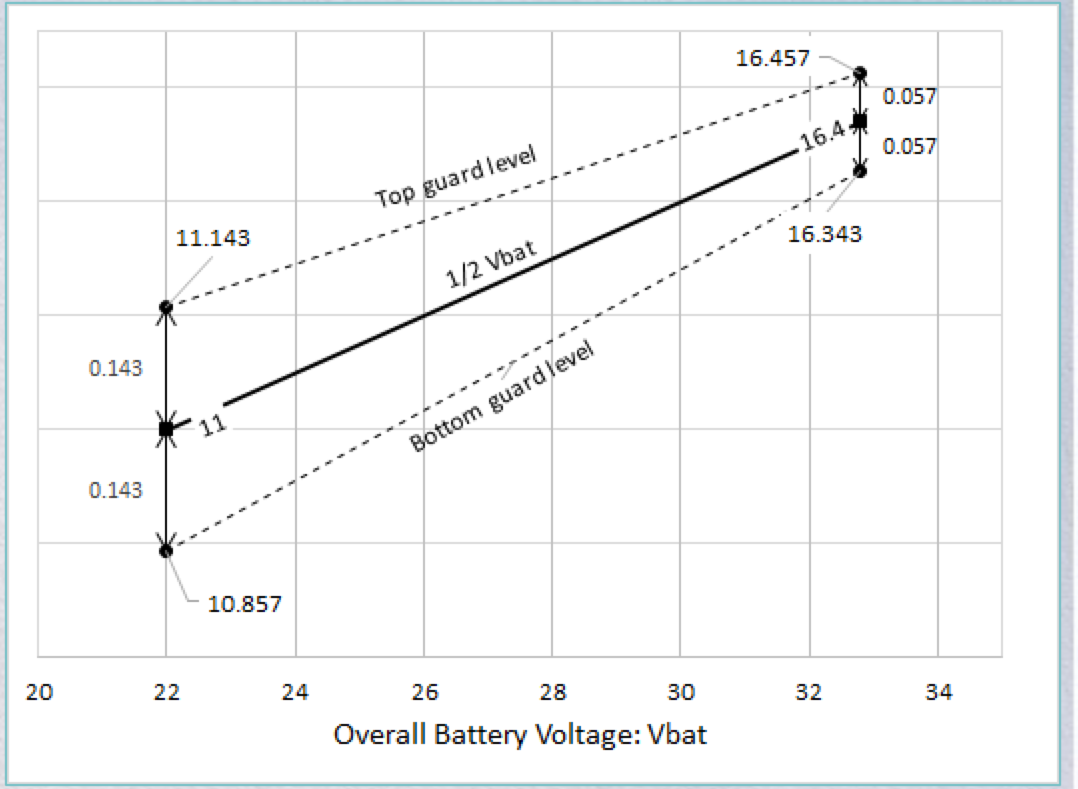
- Some applications benefit from S before P architectures (vs P before S)
  - High voltage / power applications where individual cell fusing current would be too high to protect against circulating currents during Thermal Runaway in a P-S configuration
- The xEMU project selected a modular 28V battery design to improve operational reliability and minimize sparing requirements for long duration missions
  - Uses multiple batteries in parallel to provide power to primary systems
  - Uses single battery to power secondary system in the event of a primary system failure
- Human spaceflight battery safety requirements demand redundant detection of battery conditions which can lead to catastrophic failure
  - Battery voltage monitoring during servicing provides primary control
  - A secondary control must detect cell over/under charge, imbalance, and degradation
    - Individual cell monitoring can increase latent power draw and battery design complexity, size, and mass, each of which is undesirable for xEMU
    - A midpoint method is under development for S-P applications which does not impact battery reliability, stored power consumption, and uses ½ string sub-groupings
- The Midpoint method is introduced and an initial assessment performed for the likelihood of false-alarms and failures-to-detect for normally behaving cells

Midpoint Monitoring on an 8S Battery
V_{mid} must fall within with ½ V_{bat} +/- V_{guard} (the "Guardband")

- Vguard is based upon the maximum single cell divergence that can occur without exceeding manufacturers' cell voltage limits
- Vguard depends on voltage range

For a 22 V to 32.8 V maximum range,
- Vguard is +/- 0.057 V at top of charge
- Vguard is +/- 0.143 V at bottom of discharge
- Vguard assumed to be linear in between.

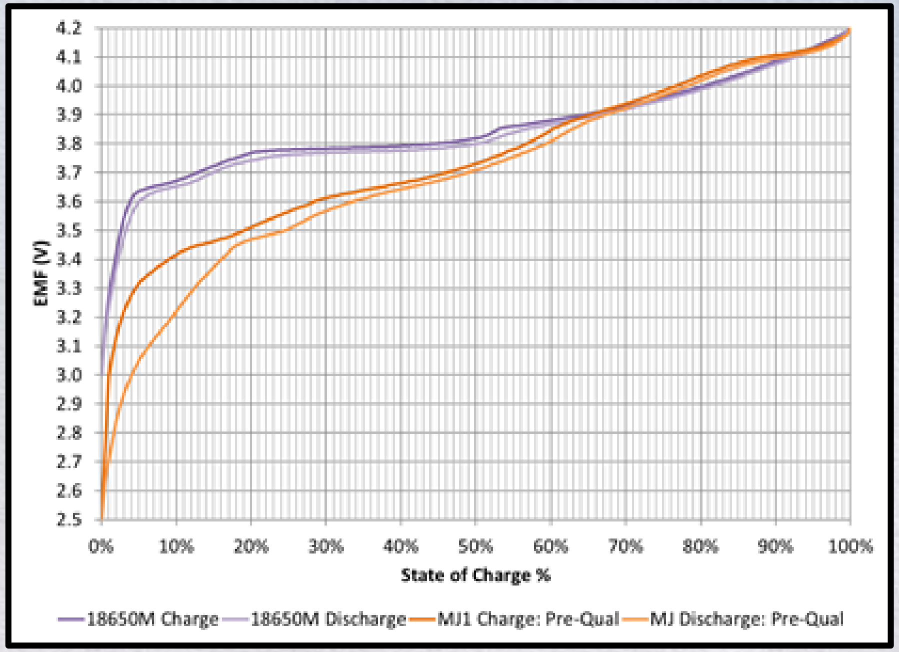




Vmid at Low and High State of Charge (SOC)

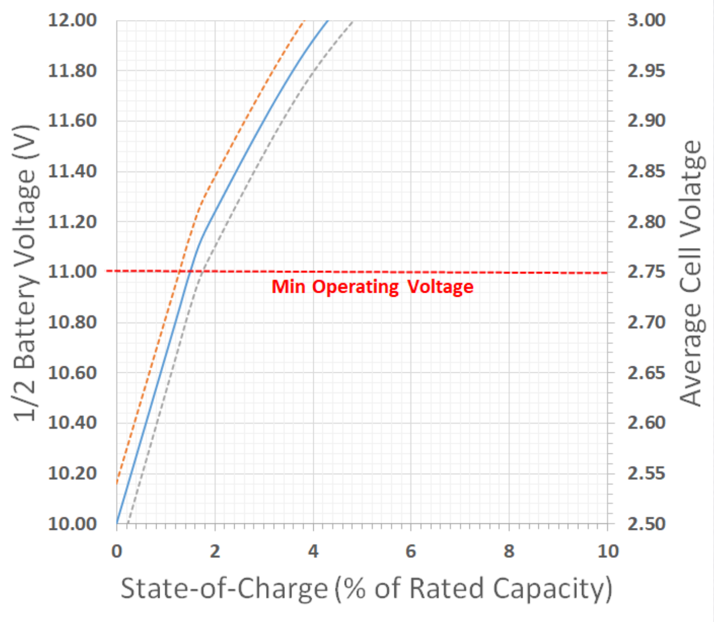
Charge and discharge voltages are nearly linear and coincident at high SOC
Voltages are highly non-linear at low states of charge

LG MJ1 and Moli M Charge/Discharge

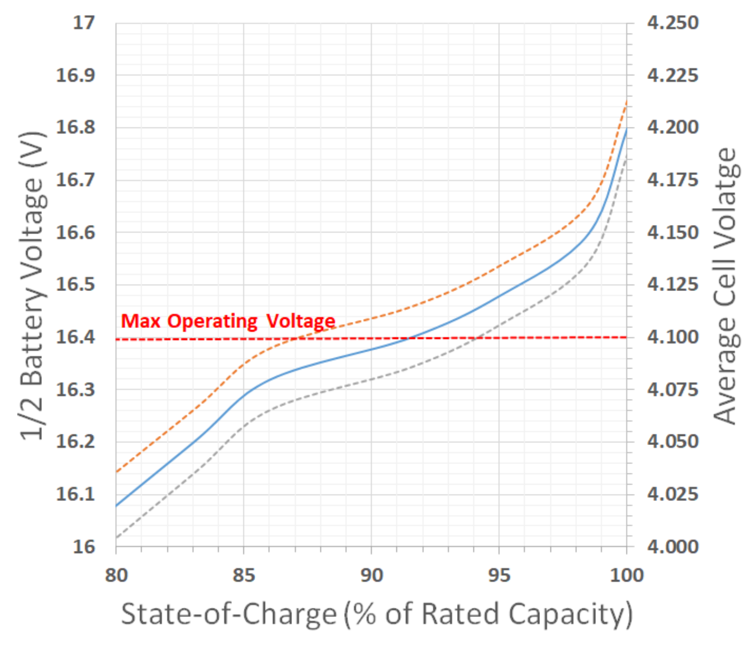


0.143 V Guardbands provide margin for ~ +/- 0.3% SOC variance at low SOC
→ *Risk of false positives could led to early termination if applied during discharge*

MJ1 Vmid with Guardband, Low SOC



MJ1 Vmid with Guardband, High SOC



0.057 V Guardbands provide margin for ~ +3% and -5% SOC variance at high SOC
→ *Cell screening and balancing at top of charge should reduce risk of false positives*

Guardbands provide margin for imbalance and capacity variance at high SOC
Guardbands provide less margin at low SOC due to non-linearity
→ ***Risk of false positives and failure-to-detect will be greater at low SOC***

End of Discharge (EOD) Loaded Voltage Spread

- Based on cycle data for an 8S string of MJ1 cells discharged to a battery voltage of < 22 V at C/5

- EOD Closed Circuit (Loaded) Voltage spread might be as high as ~ 0.3 V after 100 cycles

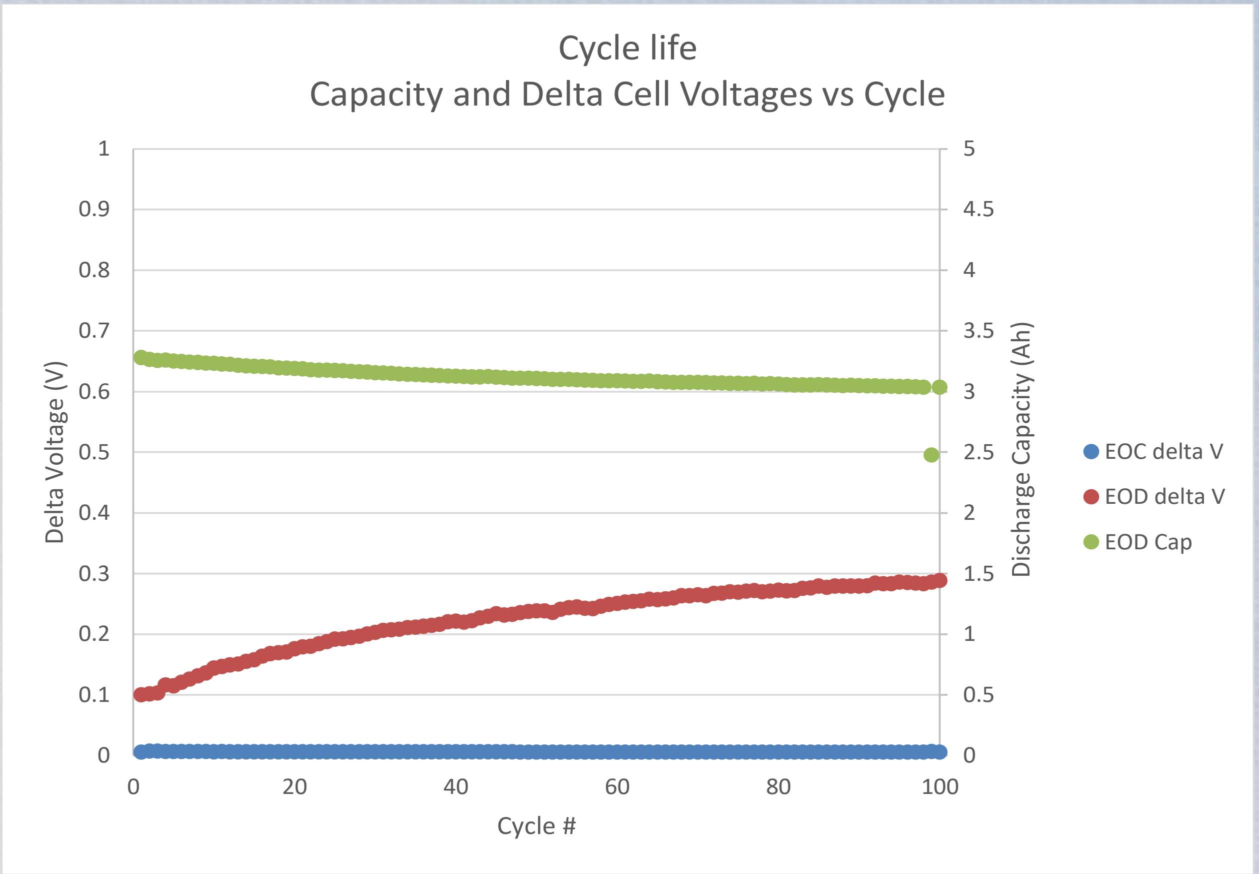


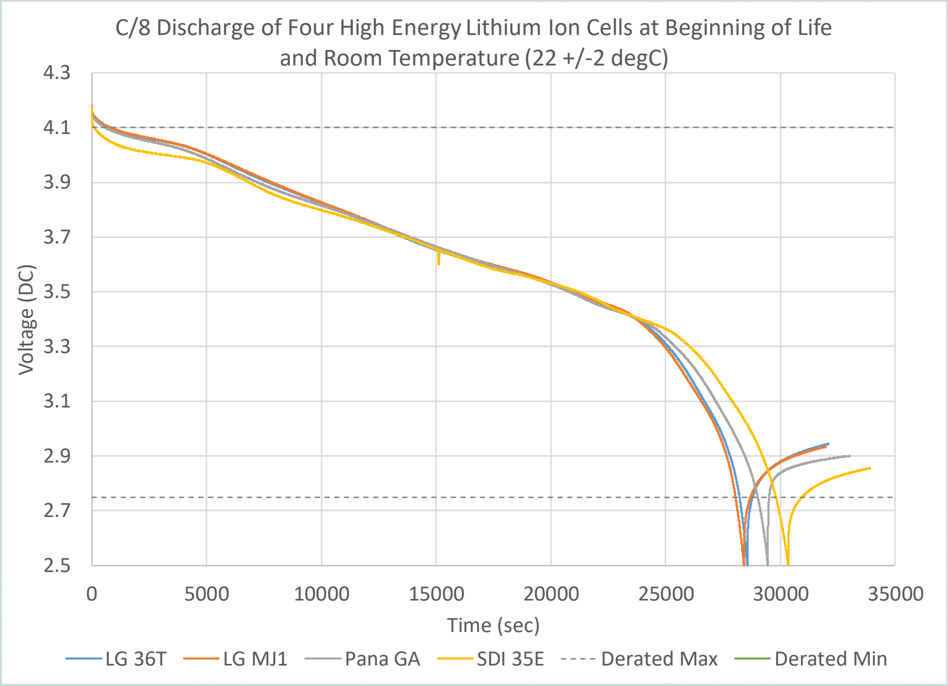
Figure 6-1: Discharge Capacity and Delta Cell Voltage vs. Cycle

Cell Divergence during cycling LG Chem MJ1 8S1P Module
Discharge to <22 V at 0.5 A (C/5)
(Eagle Picher Data)

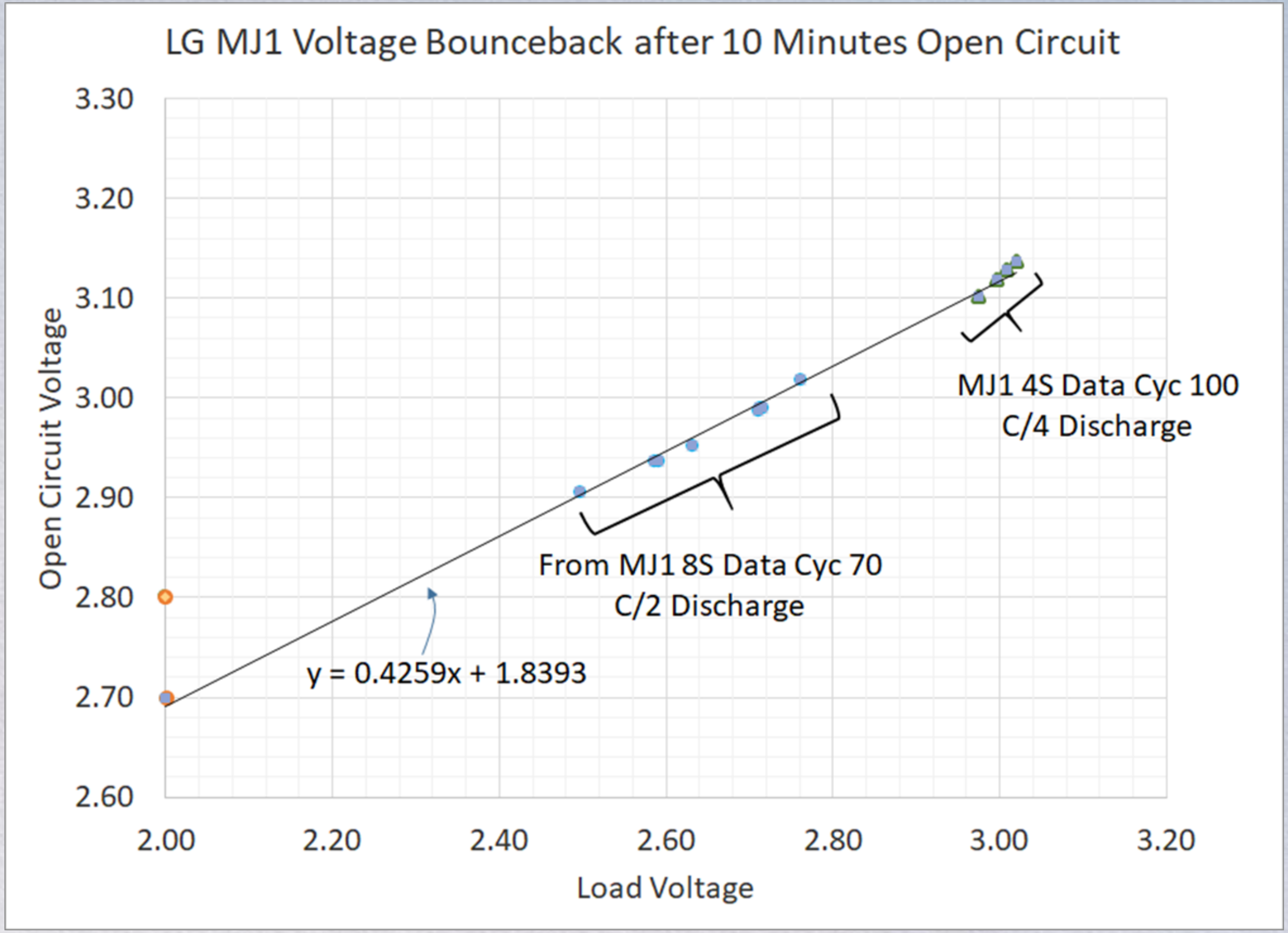
EOD Unloaded Voltage Spread at 10 Minutes

Voltage bounce-back on open circuit reduces observed loaded voltage spread

10min performance is assumed to be a linear relationship between OCV (unloaded) and CCV (loaded)



From filename "Cell Comparison.xlsx"



MJ1 OCV at 10 min is 70% of 1 hr from 2.5 V

… at C/8 is 60% of C/2 value from 2.5 V

… at C/8 is 75% of C/2 value from 2.0 V

based on review of various data files

Summarizing The Challenge

- The lithium-ion cell voltage profile is highly non-linear at low SOC even for normally operating cells
- Small (~1%) differences in inherent cell capacity or state-of-charge imbalance can create large (~300 mV) deviations in loaded voltage at low SOC (< 3 V/cell)
- Open Circuit Voltage (OCV) deviations are expected to be less due to voltage bounce-back when the load is removed, but performance will vary by cell type/manufacturer, usage, temperature, and EOD voltage
- The effects of EOD voltage non-linearity on Midpoint detection algorithms were explored, to determine potential impacts of Guardband settings on the probability of false-alarms and failures-to-detect
- A Monte Carlo simulation of <u>normal, random</u> cell voltage spread at low states of charge was examined

Monte Carlo Simulator Assumptions

- The Monte Carlo simulation is based on Excel’s random number generator, and that approach accurately predicts normal cell variance
- The End of Discharge Voltage (EODV) variance examined in the Monte Carlo simulation is for normal (i.e. non-degraded) cells, and reflects minor variances in cell capacity and EOD impedances expected with normal cell behavior
- The Monte Carlo simulation emulates a random distribution of cell voltage variance at the end of discharge. This has been verified for at least one cell type (LG MJ1) in an 8S string.
- The Monte Carlo simulation does not attempt to simulate a condition where a single degraded or failing cell is falling out-of-family from the rest of the string

Monte Carlo Simulator Structure

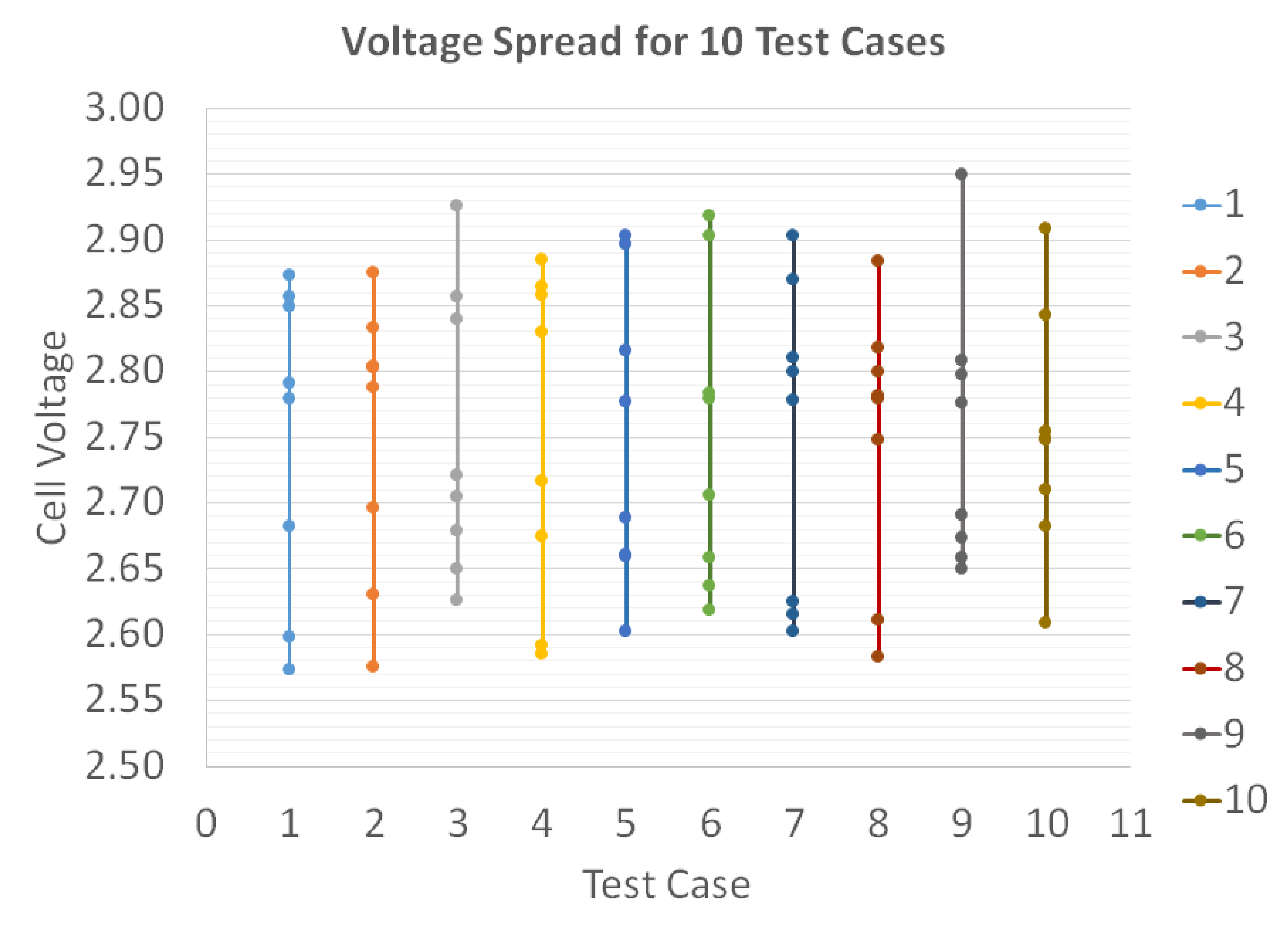
Loaded Voltage Spread	0.1			Total Cases Analyzed	1000
Battery Voltage	22			Number of cases that triggered algorithm	0
Guard Band	0.143			Number of triggered cases with Min cell V > 2.5 V under load	0
				Number of triggered cases with Min cell V > 2.75 V under load	0
				Number of non-triggered cases with Min cell V < 2.5 V under load	0
				Minimum Cell V for non-triggered cases	

Loaded Voltage Spread	0.3			Total Cases Analyzed	1000
Battery Voltage	22			Number of cases that triggered algorithm	24
Guard Band	0.143			Number of triggered cases with Min cell V > 2.5 V under load	24
				Number of triggered cases with Min cell V > 2.75 V under load	0
				Number of non-triggered cases with Min cell V < 2.5 V under load	0
				Minimum Cell V for non-triggered cases	

- INPUTS
  - String Voltage under load (V)
  - Voltage Spread under load (V)
  - Guard Band (V)
- METHOD
  - Uses Excel Random Number Generator
  - Random number from 0 to 1 for each cell location
  - Scale random range for defined voltage spread
  - Apply voltage spread to average load voltage
  - Calculates open circuit voltages based on bounce-back
  - Guard band checks are against open circuit voltages
  - 1000 test cases per calculation
- OUTPUTS
  - Total Cases Analyzed
  - Number of cases that triggered algorithm
  - Number of triggered cases with Min cell V > 2.5 V under load (False Alarms)
  - Number of triggered cases with Min cell V > 2.75 V under load (for information)
  - Number of non-triggered cases with Min cell V < 2.5 V under load (Failures to Detect)
  - Minimum Cell V for non-triggered cases (to understand just how much risk is incurred for failures to detect)

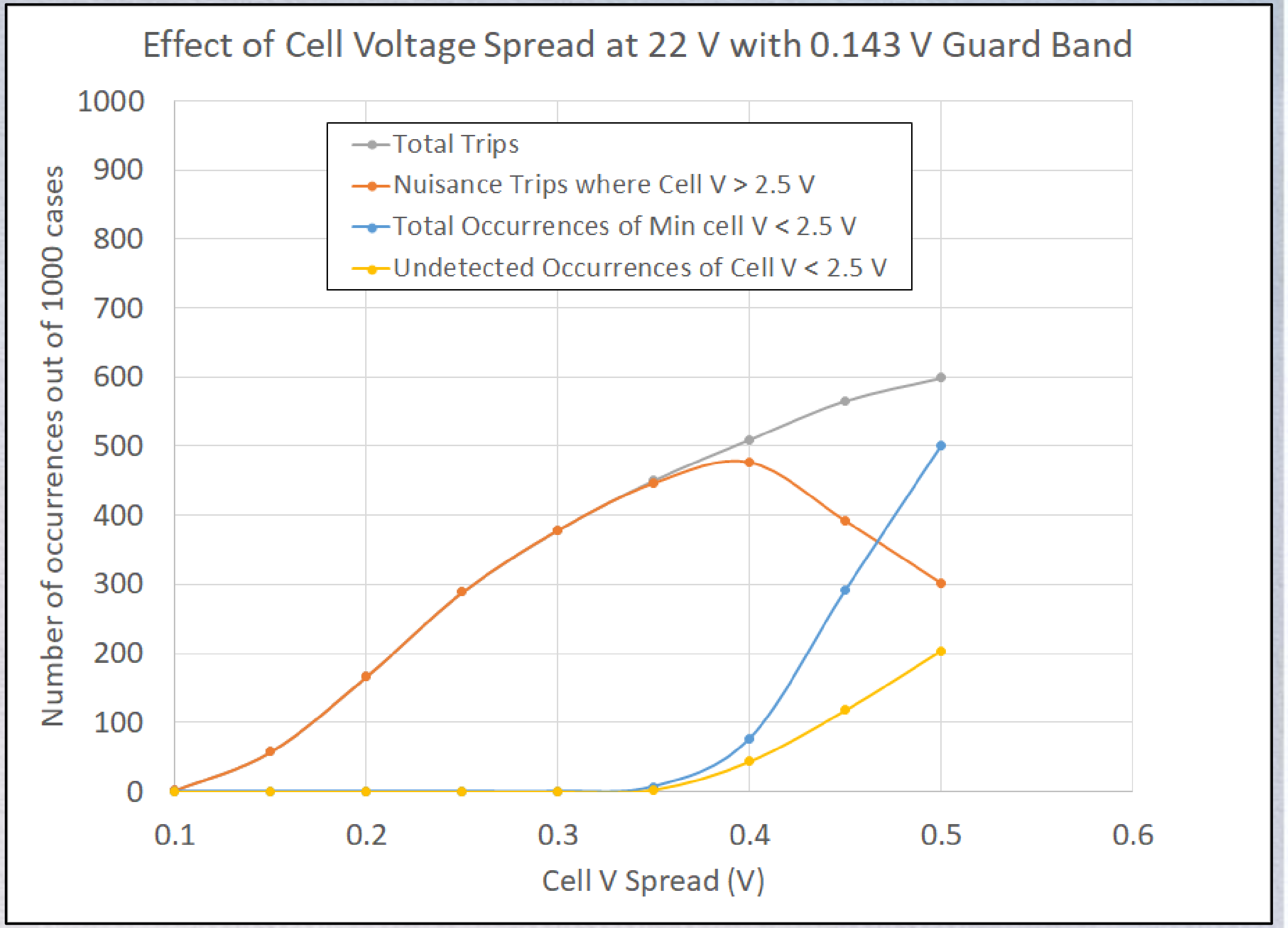
Monte Carlo Simulations Assuming Guardbands Applied During Discharge (i.e. under load)

Example of Random EOD Voltage Distributions under Load: 22 V EODV, 0.3 V Spread



Effect of EODV Cell Voltage Spread: 22 V Battery Voltage and 0.143 V Guardband, Closed Circuit

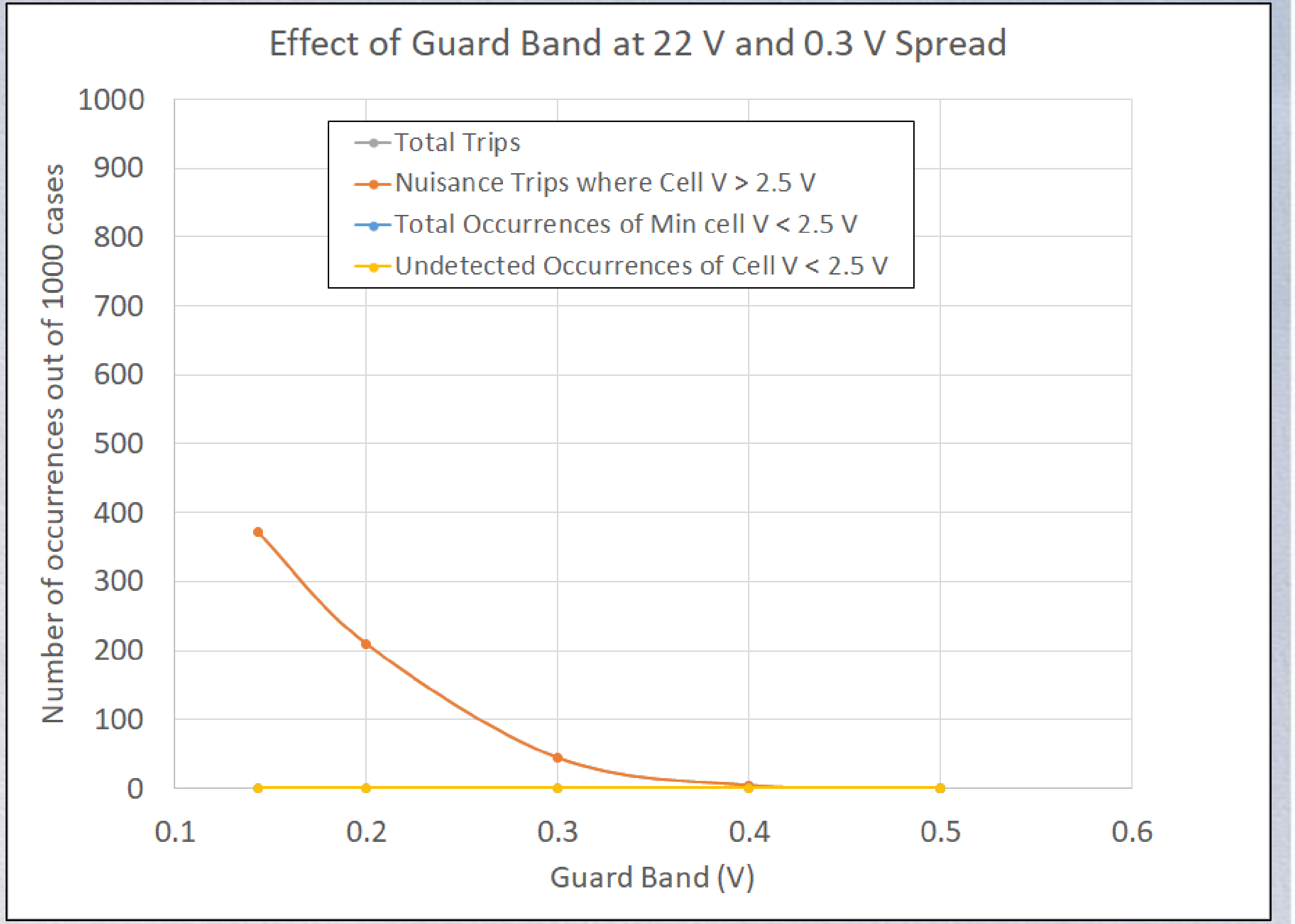
- With Guard band of 0.143 V, the algorithm will have a large number of nuisance trips (false positives) even though there are no cells below 2.5 V
- The nuisance trips increase with the amount of voltage spread, and are due to the random location of high/low V cells within the top and bottom half, which can generate variations from midpoint voltage exceeding 0.143 V
- Nuisance trips will happen ~ 38 % of the time if EODV spread is ~ 0.3 V
- Likelihood of actual Cell V < 2.5 V is minimal below normal EODV spread of ~ 0.32 V
- Above EODV spread of ~ 0.32 V, likelihood of Cell V < 2.5 V increases, 40 % of those cases will go undetected due to “masking”



Effect of Widening Guardband
22 V Battery Voltage and 0.3 V EODV Spread, Closed Circuit

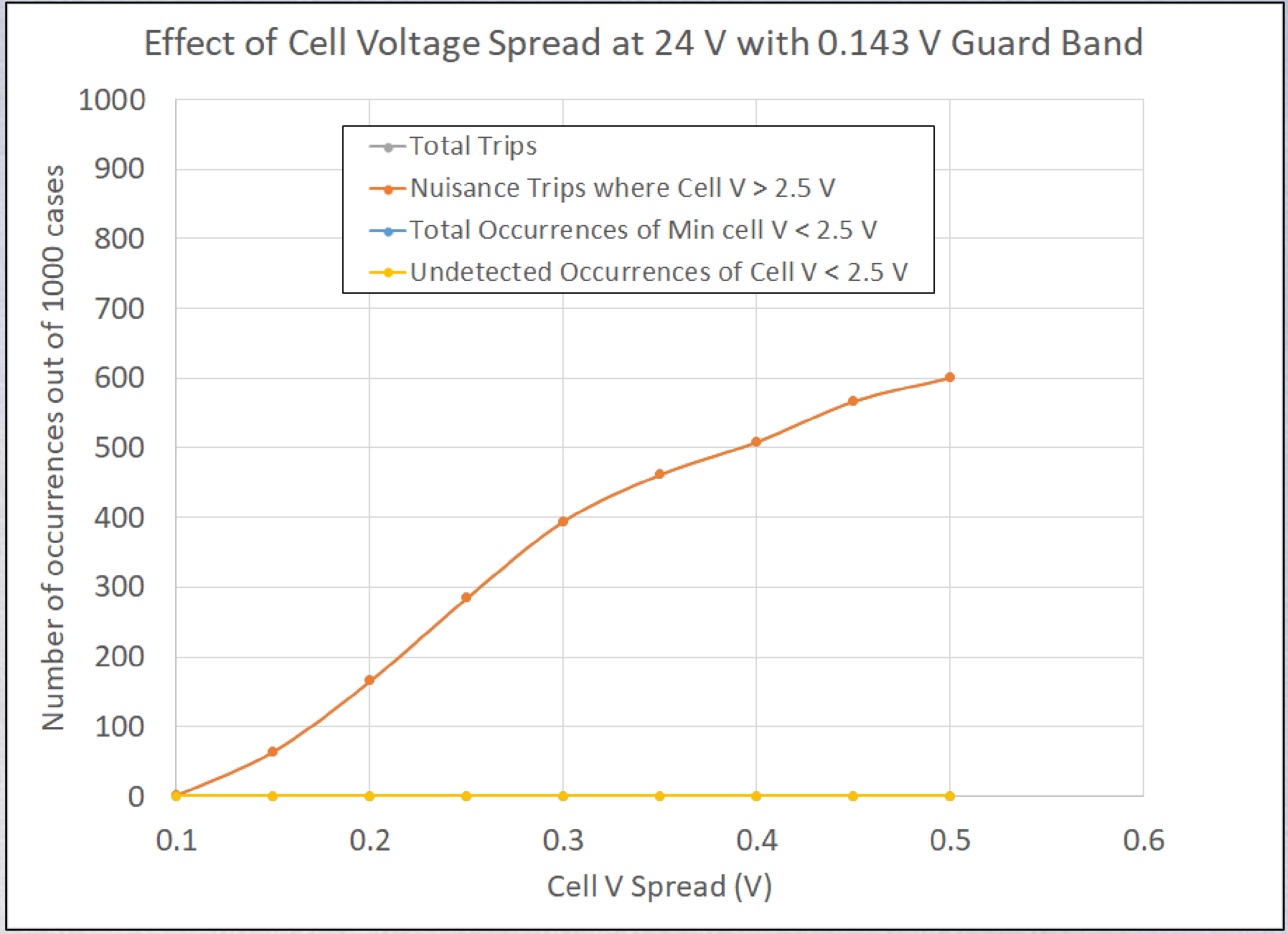
- Number of nuisance trips declines as Guard band is widened, as expected

- For a EODV spread of 0.3 V, widening the guard band to ~ 0.4 V at 22 V battery voltage will effectively eliminate nuisance trips



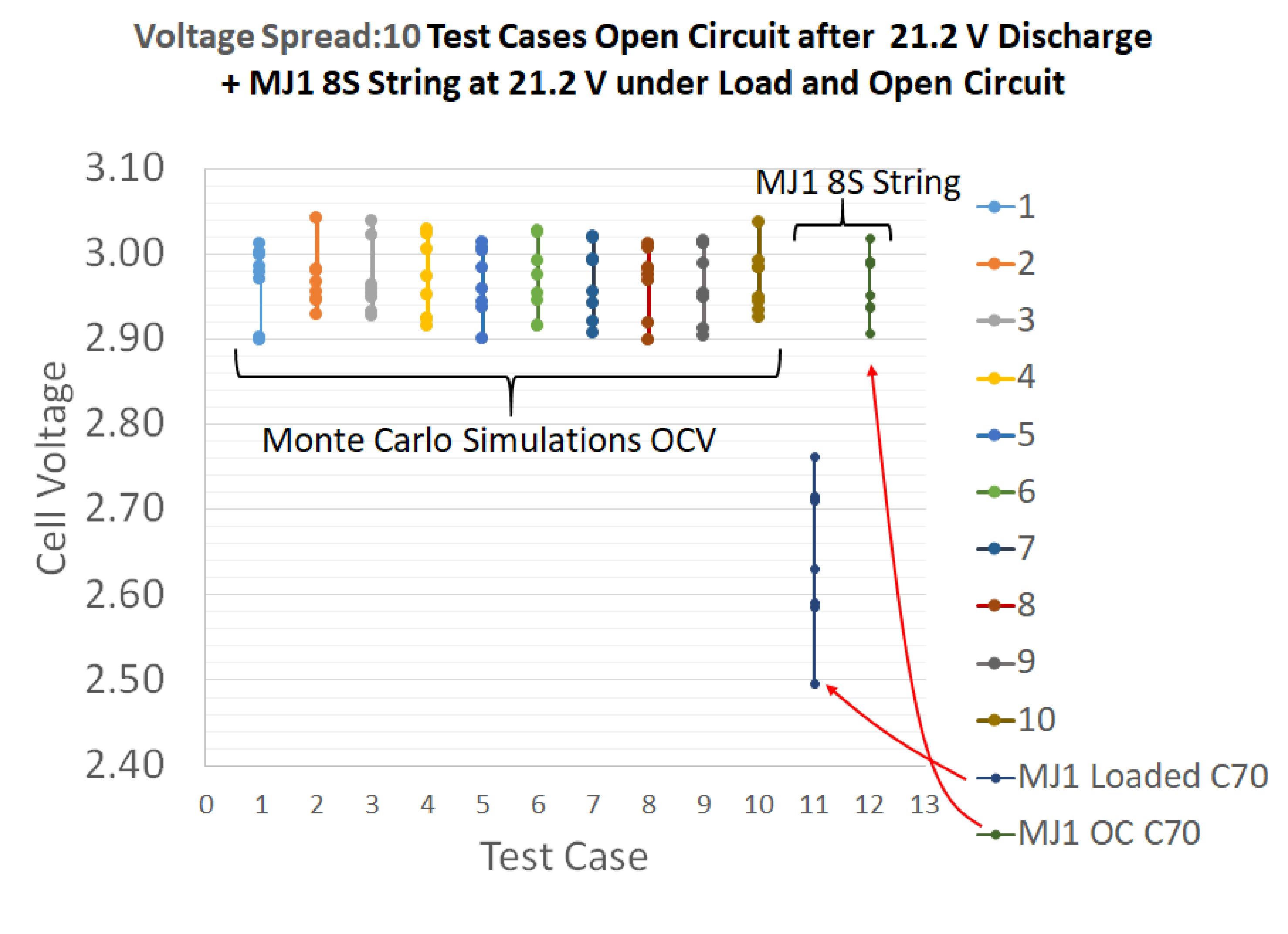
Effect of Increasing Discharge Cutoff Voltage
24 V Battery Voltage and 0.143 V Guardband, Closed Circuit

- At 24 V, likelihood of actual Cell V < 2.5 V is near zero, even for normal EODV spreads to 0.5 V; *risk of failure-to-detect is also near zero*
- With Guard band of 0.143 V, the algorithm will still have a large number of nuisance trips (false positives) even though there are no cells below 2.5 V
- The nuisance trips increase with the amount of voltage spread, and are due to the random location of high/low V cells within the top and bottom half, which can generate variations from midpoint voltage exceeding 0.143 V
- Nuisance trips will happen ~ 40 % of the time if EODV spread is ~ 0.3 V



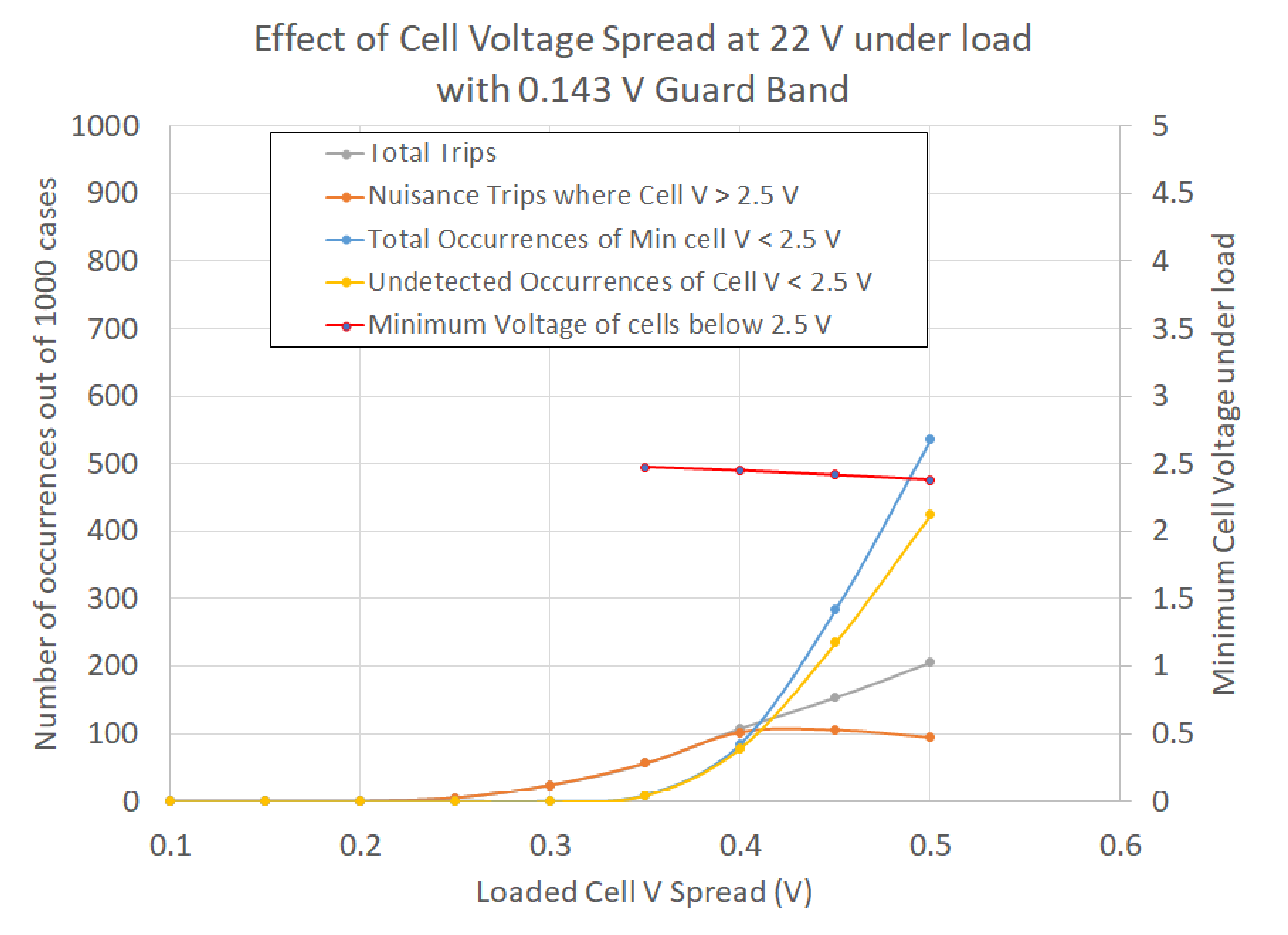
Monte Carlo Simulations Assuming Guardbands Applied During Open Circuit (i.e. after discharge is halted)

Example of Simulated Cell Voltage Distributions for MJ1 8S String on Open Circuit after discharge to 21.2 V average with 0.264 V Spread under Load



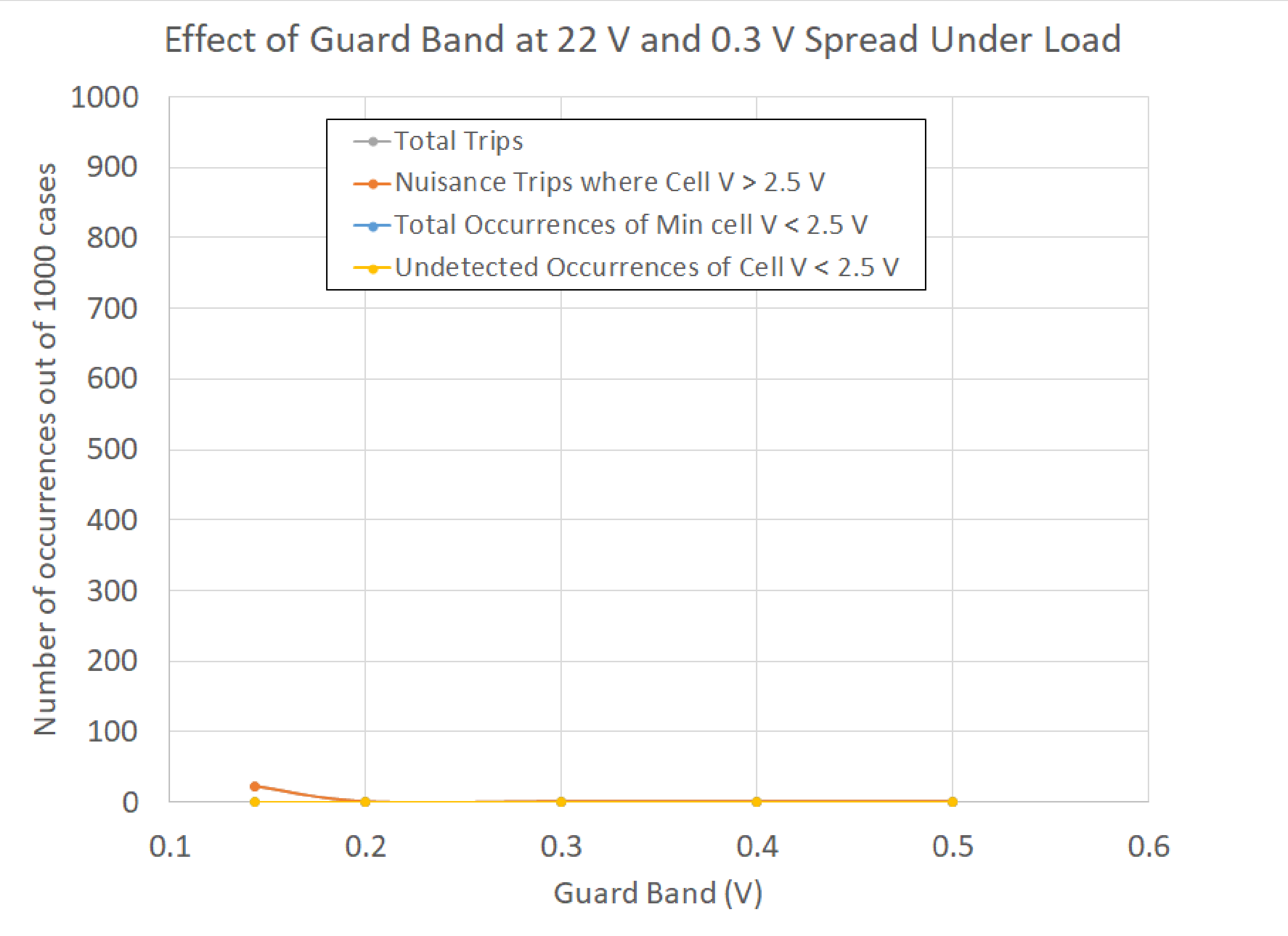
Effect of Loaded Cell Voltage Spread
0.143 V Guardband applied on open circuit after bounce-back
22 V discharge limit under load, linear bounce-back correlation

- With Guardband of 0.143 V, the algorithm will have below ~ 10 % nuisance trips for all loaded voltage spreads
- With Guardband of 0.143 V, the algorithm will have ~ 3% nuisance trips for a loaded EODV spread of ~ 0.3 V after 10 min of bounce-back
- Likelihood of actual Cell V < 2.5 V under load is minimal below normal EODV spread of ~ 0.32 V under load
- Above EODV spread of 0.33 V under load, some normal cell voltages are expected to be below 2.5 V
- A large percentage of cases where EODV cell voltage is actually < 2.5 V under load will go undetected, due to “masking”
- HOWEVER, the undetected cells are not significantly below 2.5 V



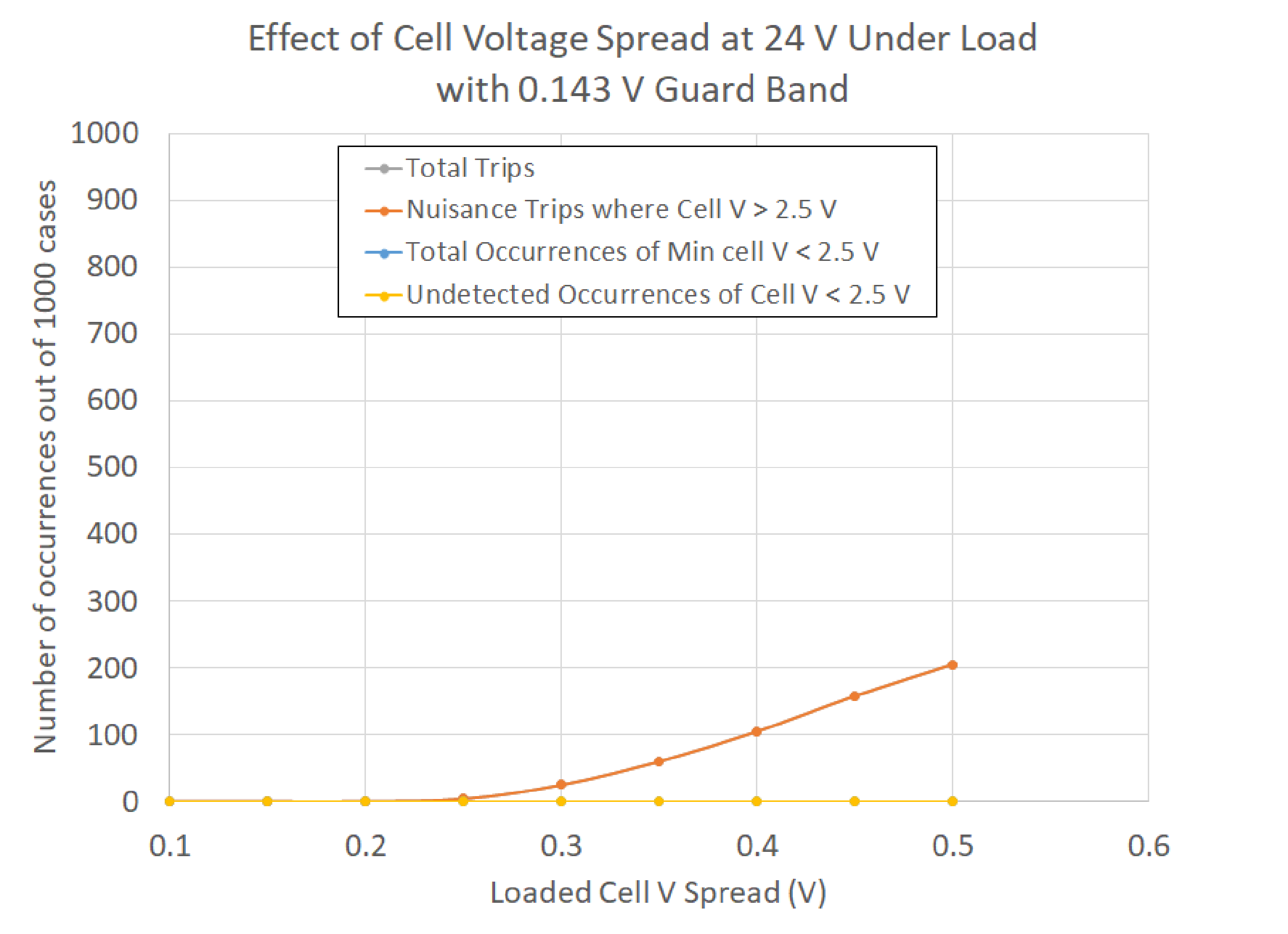
Effect of Widening Guardband on Open Circuit
22 V discharge limit under load, linear bounce-back correlation
0.3 V Loaded Voltage Spread

- Widening Guard band to ~0.200 V on open circuit effectively eliminates any risk of nuisance trips.



Effect of Increasing Discharge Cutoff Voltage
24 V Discharge and 0.143 V Guardband, Open Circuit

- At 24 V, likelihood of actual Cell V < 2.5 V is near zero, even for normal loaded EODV spreads to 0.5 V; *risk of failure-to-detect is also near zero*
- With Guard band of 0.143 V, the algorithm will still have an increasing number of nuisance trips (false positives) above ~ 0.25 V spread, even though there are no cells below 2.5 V
- Effectively all trips are expected to be nuisance trips, unless created by an actual failing cell, which means that normal cell voltage variation can cause nuisance trips that cannot be ignored
- The nuisance trips increase with the amount of voltage spread, and are due to the random location of high/low V cells within the top and bottom half, which can generate variations from midpoint voltage exceeding 0.143 V
- Nuisance trips will happen ~3% of the time if EODV spread is ~0.3 V



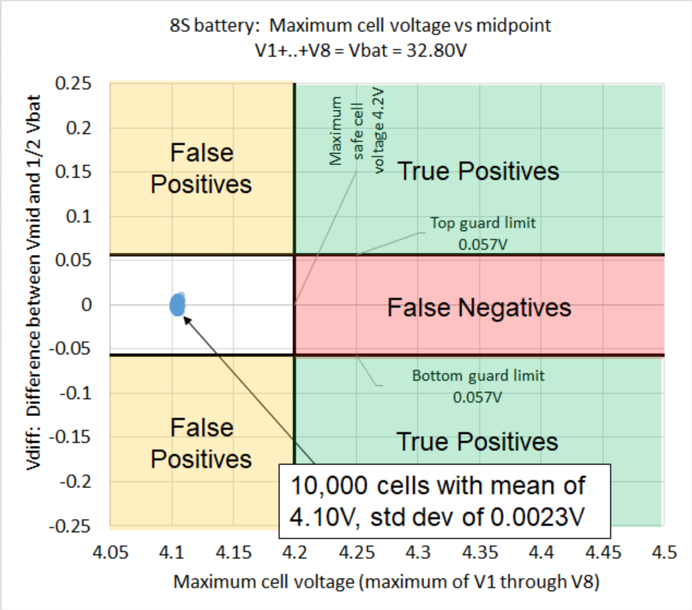
Result Summary and Initial Observations

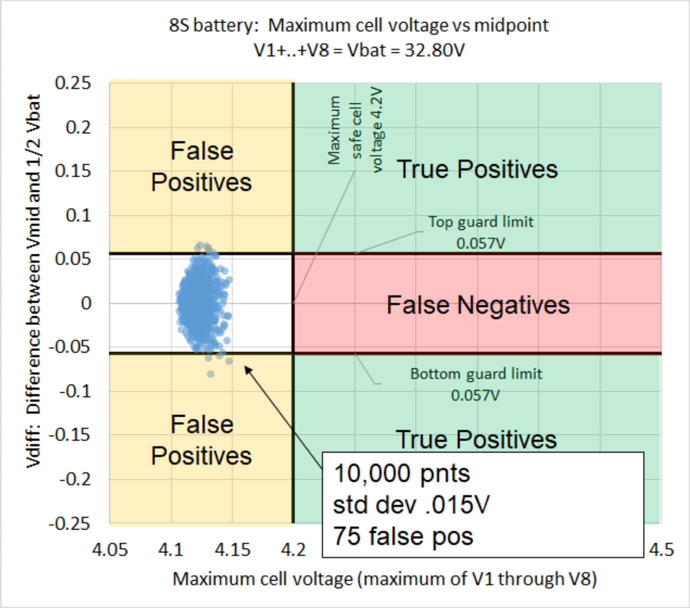
Cell	Guardband	CCV Spread (mV)	Nuisance (CCV)	Nuisance (OCV)	# < 2.5 V	# Undetected
MJ1	0.143 V	0.300 V	~ 40 %	< 3 %	0	0
MJ1	0.143 V	0.400 V	~ 47 %	~ 10 %	~ 8%	> 50 %
MJ1	0.200 V	0.300 V	~ 20 %	~ 0 %	0	0
MJ1	0.400 V	0.300 V	~ 0 %	0	0	0

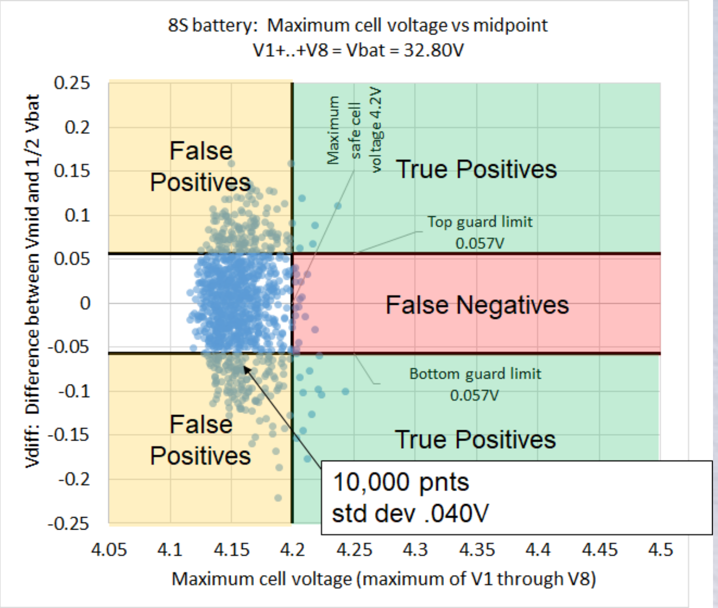
- Guardband value selection needs to consider loaded vs unloaded scenarios
- Disabling Guardbands below 10% - 20% SoC would eliminate nuisance trips
  - The concomitant increase in failure-to-detect risk can be reduced by increasing discharge cut-off voltage (e.g. to 24 V)
- Guardband values are cell type and battery usage specific
  - Voltage spread and bounce-back will be different for other cell types due to different EODV decline curves and resistance

Forward Work

- Assess guardband application to different cell types and usage conditions
  - Collect CCV and OCV spread data, for each cell type, over a range of discharge rate, EOD voltages, voltage relaxation time, cycle count, and temperature if needed
  - Develop operational guardband values suitable for charge and discharge over mission life, and identify cell performance (screening) requirements if necessary
  - Extend analysis to cell failure scenarios
- Verify statistical assumption on false-positive and failure-to-detect predictions
  - A normal distribution without a tail of bad cells leads to extreme numbers of false positives







Limitations of Midpoint Method

Factors that limit the applicability of the midpoint method:

- Number of cells in a string:
  - While the midpoint monitoring technique can work with an odd number of cells if the guard bands are adjusted, a large number of cells decreases size of the guard bands, making implementation more difficult for high voltage batteries.

- Margin between operational and safety limits:
  - The gap between the guard bands depends on the gap between the operational and safety limits. Increasing the maximum operational limit until it is equal to the maximum safe limit increased performance but makes the midpoint method unusable. It may be feasible to increase the margin by performing cell safety tests that allow a larger value to be used for the safety limit, thus increasing the gap.

- Uniformity of cell characteristics:
  - **Midpoint monitoring relies on the cells having uniform characteristics**. A large variation in cell characteristics will translate into a large difference between ½ Vbat and Vmid. This means that the midpoint method is not suitable for use with batteries made from cell lots that have not been screened intensively.

- Reliability of cells:
  - There is a small probability that two bad cells can hide each other, and neither be detected by the midpoint method. This probability grows rapidly if the probability of a single cell failure is increased. This means that the midpoint method is most suitable for cell designs that have a field history that allows an estimate of the probability of single cell failure.

Limitations of Midpoint Method

Factors that limit the applicability of the midpoint method:

- Accuracy and stability of voltage measurements:
  - Uncertainty in the voltage measurements can cause the midpoint monitoring method to falsely indicate a problem (more likely), or ignore a problem (less likely). This means that the charger and charge cabling must be carefully designed and tested to ensure accurate and stable measurements.
- Cell Overdischarge characteristics:
  - Variation in the characteristics of cells in the overdischarge region will create large deviations in the midpoint method, which may create nuisance trips. Production lots of cells intended for use in batteries which will be monitored with the midpoint method should be tested for this variation.
- Charger induced imbalance:
  - If the charger is not properly designed, it can imbalance the battery by sourcing or sinking current to or from the midpoint sense line. Chargers and battery monitoring systems can also imbalance batteries through sense lines, so this is not unique to the midpoint method. The midpoint method as described here does not have a method of rebalancing the battery. However, the charger must be carefully designed and tested to ensure that it will not imbalance batteries through the midpoint.
- Thermal gradient and impact on cell aging:
  - It is possible for thermal gradients in a battery to create undetectable changes in characteristics of subsets of the cells in a battery. The thermal environment of the battery and the battery design should be analyzed to determine if this is an issue.

Acknowledgements

- The presenter acknowledges the hard work of those who performed this work:
  - G. Bayles, SAIC and F. Davies, NASA Johnson Space Center
- The tireless efforts of those who performed numerous reviews and evaluations:
  - E. Darcy and D. Delafuente, NASA Johnson Space Center
  - C. Iannello, NASA Kennedy Space Center
  - R. Bugga, Jet Propulsion Laboratory
- And most of all, the financial and leadership support provided by the Power Technical Discipline Lead of the NASA Engineering Safety Center
  - C. Iannello, NASA Kennedy Space Center

- *The contents of this presentation represent a portion of a larger body of work assessing the Midpoint Monitoring Method which will be documented in a future white paper.*