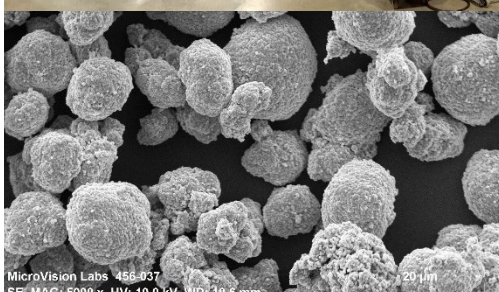
CAMX Power High Sensitivity Cell Screening Technology



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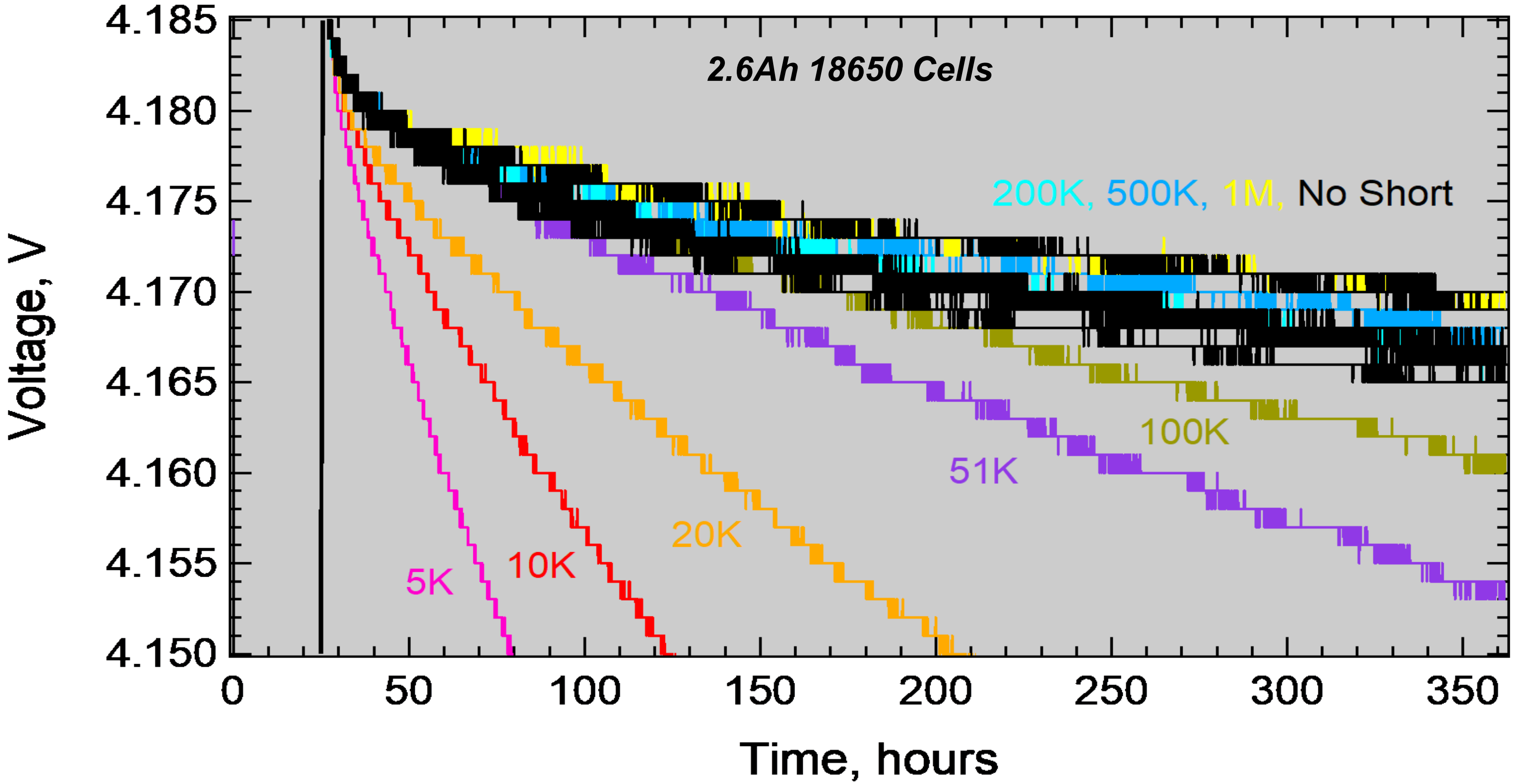
Background:

Acceptance Screening of Li-Ion Cells by the End User

- Where safety and reliability are critical, end users of Li-ion cells may carry out 100% acceptance screening against qualification metrics they select and control.
- Manufacturer QC can be an opaque process with details of specific QC protocols and metrics (and any changes made over time) not available to the end user.
- Evaluating cells for anomalous levels of self-discharge, that may indicate a risk to safety or performance, is a fundamental part of such acceptance screening.
- Standard industry practice to screen for elevated self-discharge is via cell voltage change over time (e.g., 7-28 days).
- This step dominates cell manufacturing cycle time and incurs significant costs, necessarily forcing tradeoffs between testing thoroughness and economics.
- *Given these considerations, acceptance screening of Li-ion cells via user-defined protocols and metrics can reduce risk and optimize performance.*

Typical industry QC methodology to screen cells for anomalous self-discharge uses drop in terminal voltage over time (e.g., 14 days):



➢ *This test, a 14-day hold period following formation-rate charging, shows that self-discharge resistances to ≈125,000 Ohms are distinguishable from the self-discharge-free condition, but higher resistance levels <u>would not be detected</u>.*

Monitoring cells for OCV decline over time to screen for anomalous self-discharge requires long residence times to achieve high sensitivity.

OCV Monitoring Duration	Sensitivity[1]
7 Days	≈ 50 KΩ
14 Days	≈ 100 KΩ
28 Days	≈ 200 KΩ
3 Months	≈ 650 KΩ
6 Months	≈ 1.3 MΩ
12 Months	≈ 2.6 MΩ

1. *Maccor Series 4000 Battery Test System (16-bit resolution), 2.6 Ah 18650 Cell.*

- *Manufacturers must balance sensitivity against the expense of residence time;*
- *Accordingly, some cells that ideally would have been rejected in manufacturing QC may instead get through and ship to customers.*

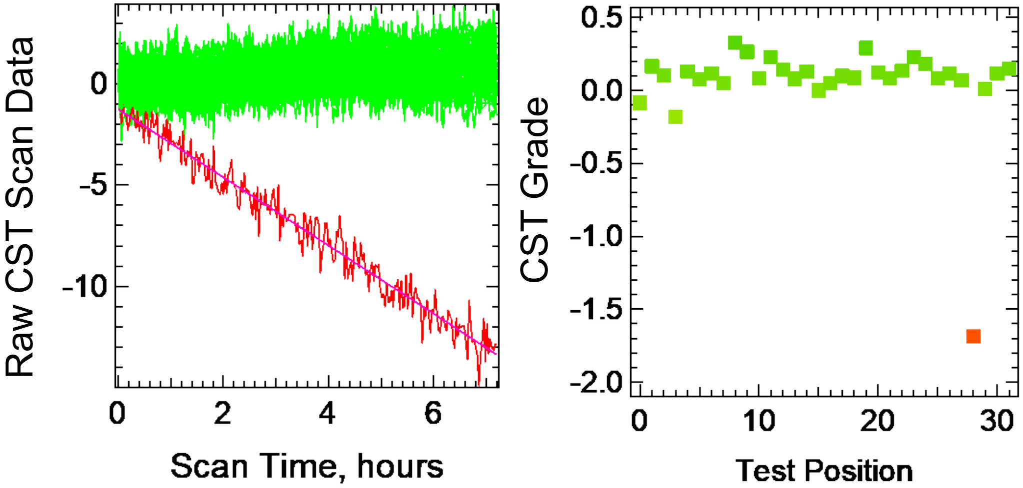
The CAMX Power High-Sensitivity Cell Screening Technology (CST)

Developed under a DLA-sponsored SBIR Program, CST combines speed, sensitivity, and convenience enabling routine, high-performance screening cells.

CST Instrument Prototype 1.0

32-Cell (18650-Format) Screening Batch Capacity

Scan Results: Commercial Cell Found to have Anomalous Self-Discharge at the ≈1MΩ Level.

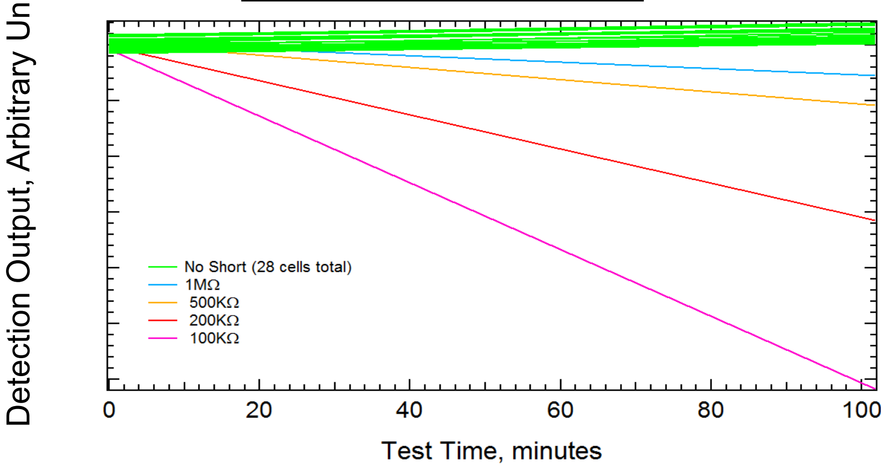


- In the scan example shown, CST detected in just hours anomalous self-discharge that would require >100 days to identify with OCV tracking over time.
- The diagnostic speed and ultra-high sensitivity of CST renders routine screening of large numbers of cells for elevated self-discharge practical and convenient.

Quantitative accuracy of CST was validated in testing on cells under rigorously controlled conditions of known levels of self-discharge.

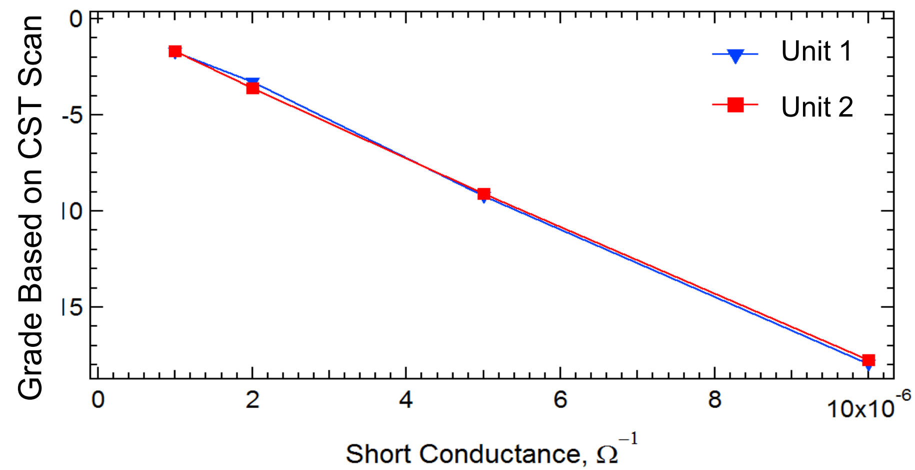
CST Results for Commercial 18650 Cells with Known Levels of Self-Discharge (Load Resistances as Surrogates) at 1MΩ, 500KΩ, 200KΩ, and 100KΩ.

Raw CST Scan Data



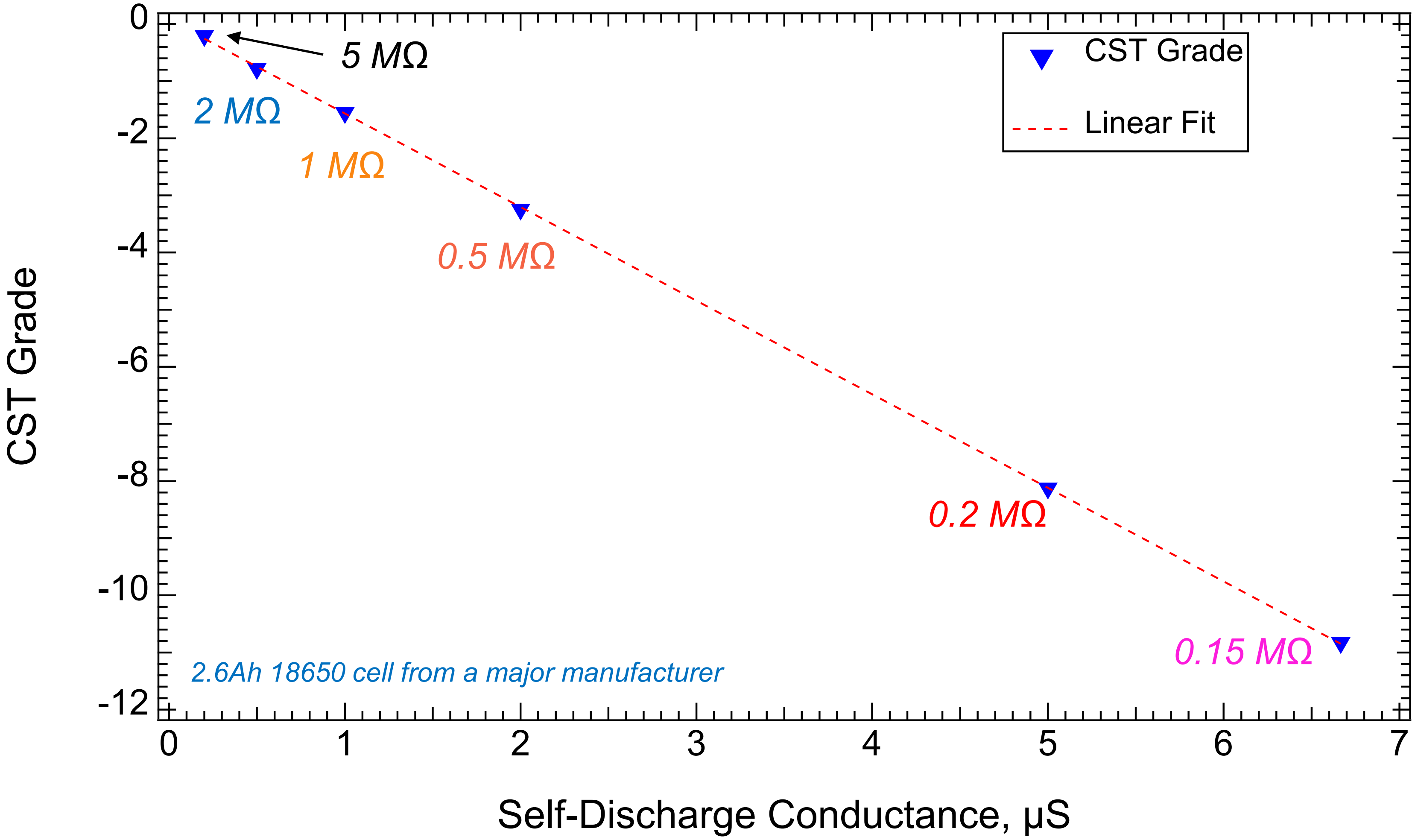
- *Slope of the CST scan data is a figure-of-merit for the CST test and also a quantitative grade of self-discharge.*
- *The more negative the slope, the more significant the self-discharge of the cell.*

CST Grade vs. Self-Discharge



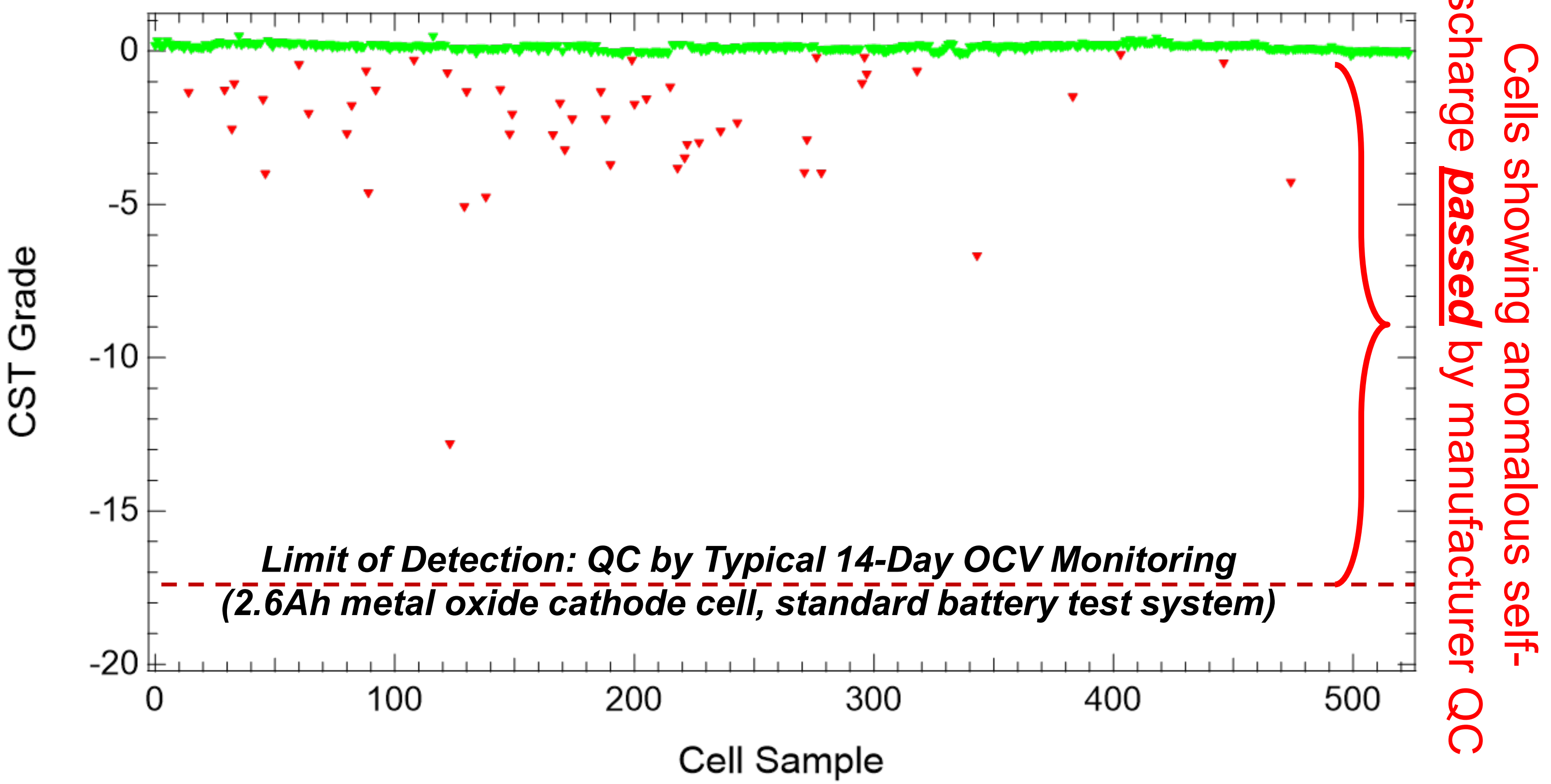
- *The tight linear relationship between CST Grade and self-discharge conductance for these two tested units illustrates the quantitative performance of CST measurement of self-discharge.*

This test shows characterization of CST detection sensitivity and quantitative accuracy to the 5 MΩ level in an 8-hour scan.



CST successfully identifies cells with elevated levels of self-discharge not identified by manufacturer QC, as shown by these results:

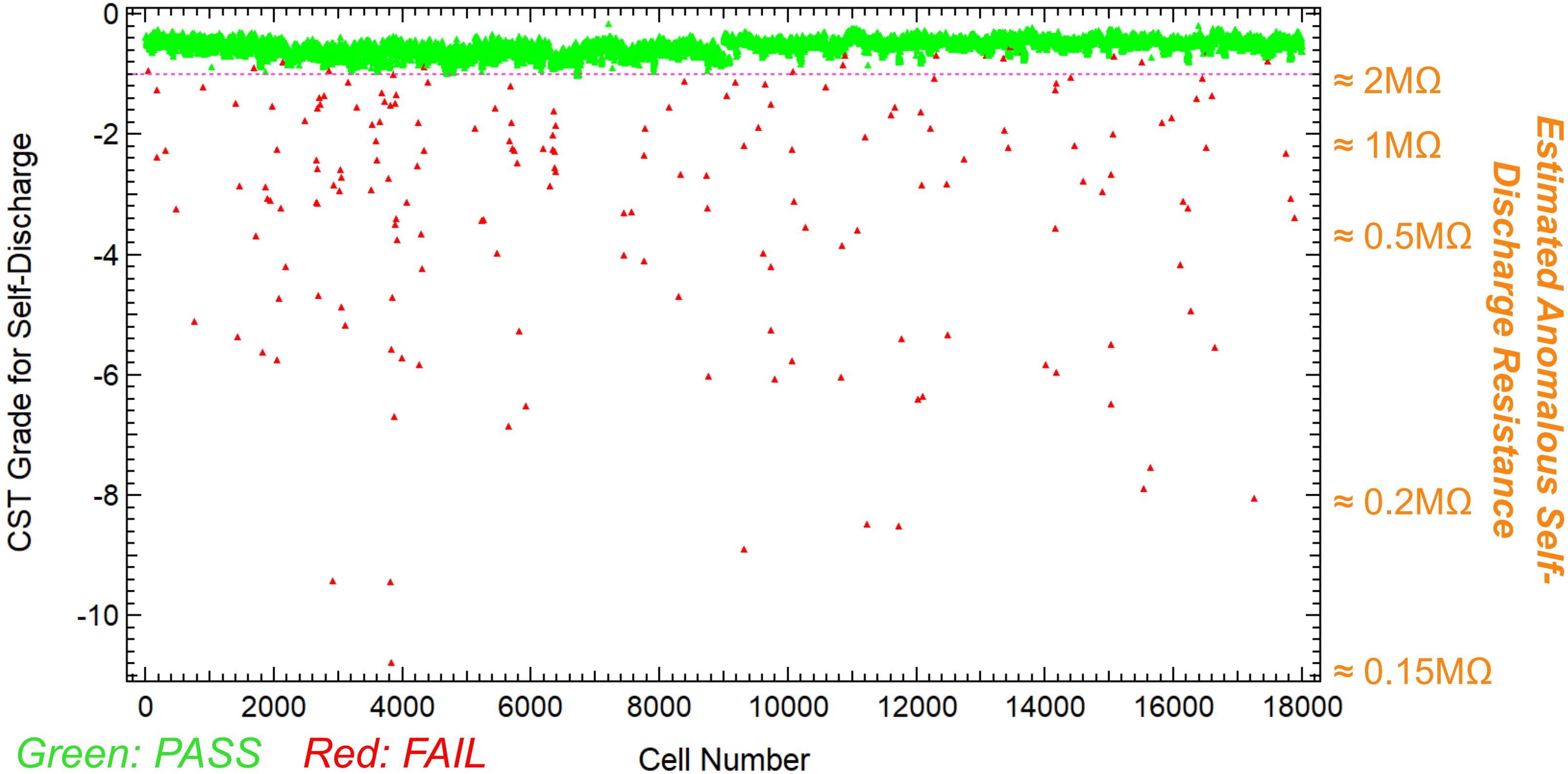
CST Screening Results for 500+ Cells



➢ *While all these cells passed manufacturer QC, high-sensitivity screening using CST identified certain cells, 10% of the group, with anomalous self-discharge.*

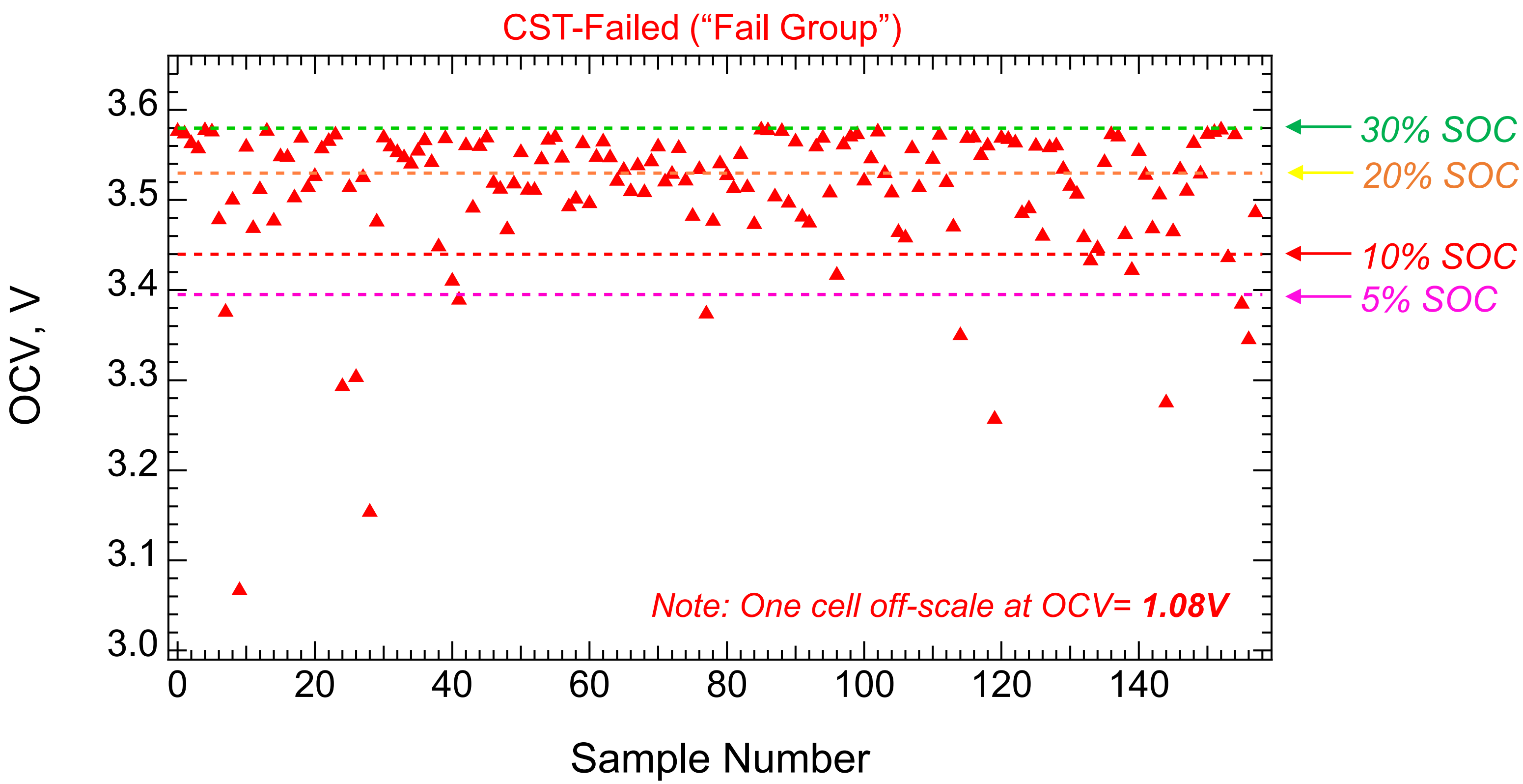
Examples of Results:
Screening of Li-Ion Cell Populations Using CST

In this example, we screened a population of 18,000 cells (18650-format), failing 189 of these cells for anomalously high self-discharge.



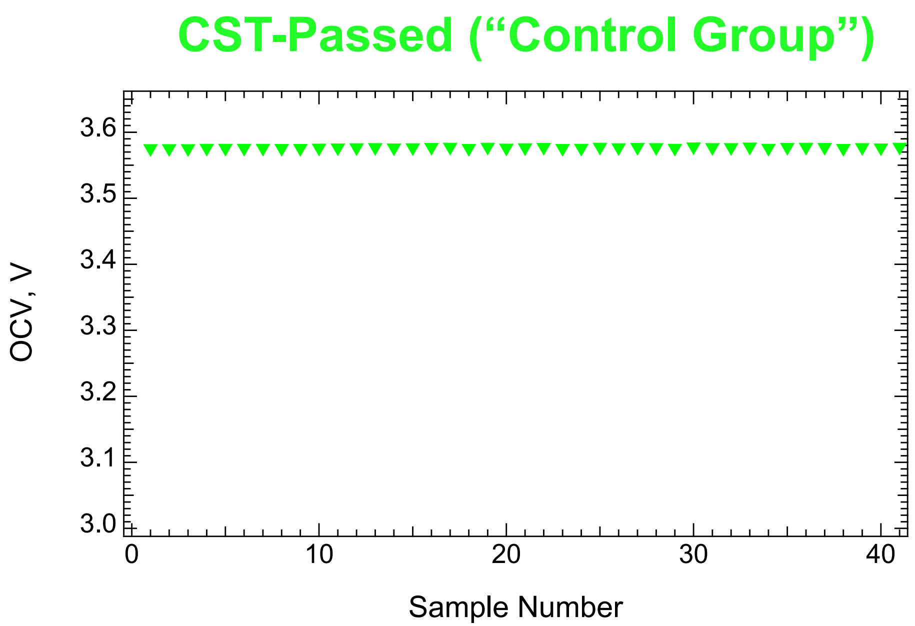
- We note that in ALL of the cells that we failed based on our CST results showed elevated self-discharge levels beyond the ≈ 0.1-0.125 MΩ detection limit we estimate for these 2.6Ah cells for 14-day hold period with OCV monitoring QC.

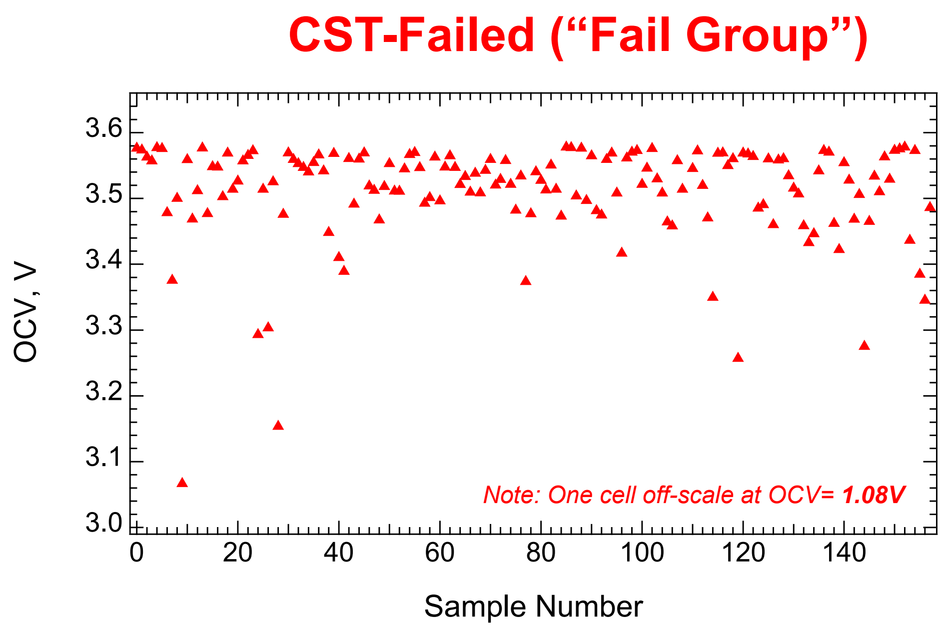
About 18 months after we screened those 18,000 cells using CST, we checked cell OCV highlighted the significant self-discharge of the CST-failed cells.



➢ OCV change over time independently confirmed the effectiveness of CST in identifying cells with elevated rates of self-discharge.

For comparison, we show here OCV data for a set of control cells (left, green markers) retained from the 18,000-cell group screened.





- The CST-passed cells showed uniform retention of OCV over time consistent with normal background self-discharge only.
- The CST-failed cells showed significant OCV loss over time with many cells approaching 0% state-of-charge and one cell failing via over-discharge.

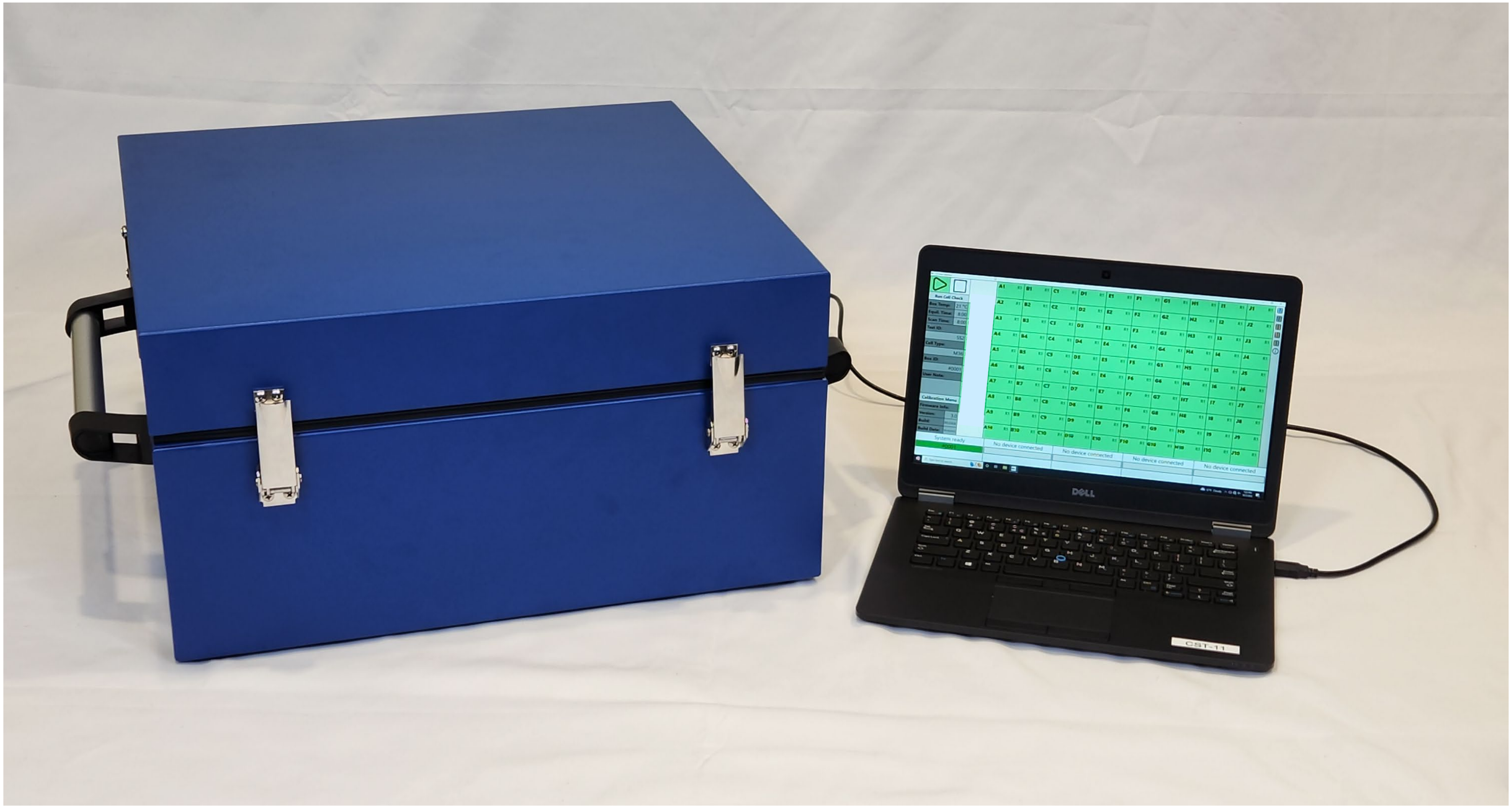
We have now screened tens of thousands of cells and, in each case, found cells within each lot showing anomalously high levels of self discharge.

Cell Type	Number of Cells in Group	Total Cells Failed
Type A 2.6Ah 18650	600	59
Type A 2.6Ah 18650	18,000	189
Type B 3.5Ah 18650	2,400	27
Type C 3.5Ah 18650	2,500	18
Type B 3.5Ah 18650	2,500	16
Type C 3.5Ah 18650	2,500	27
Type B 3.5Ah 18650	5,100	23
Type C 3.5Ah 18650	5,000	48
Type C 3.5Ah 18650	3,000	49

- *All cell types are all from major global manufacturers.*
- *Pass/fail thresholds are client-specific but generally 2-3MΩ of elevated self-discharge or CST Grade > 3 std. dev. from the mean.*

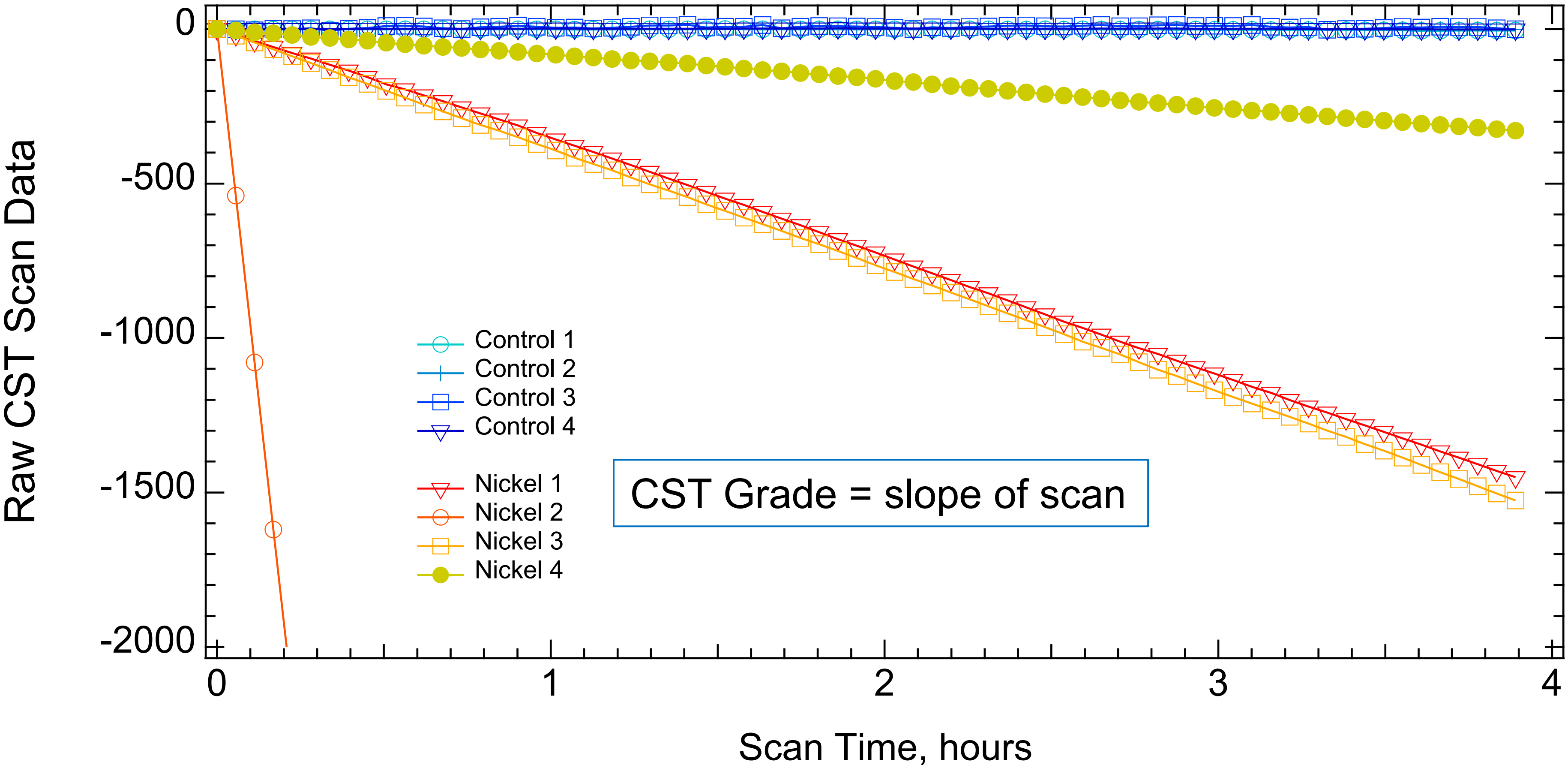
Shown here is our most recently completed CST prototype instrument.

100-Cell Capacity CST-Based Prototype 18650-Cell Screening Instrument



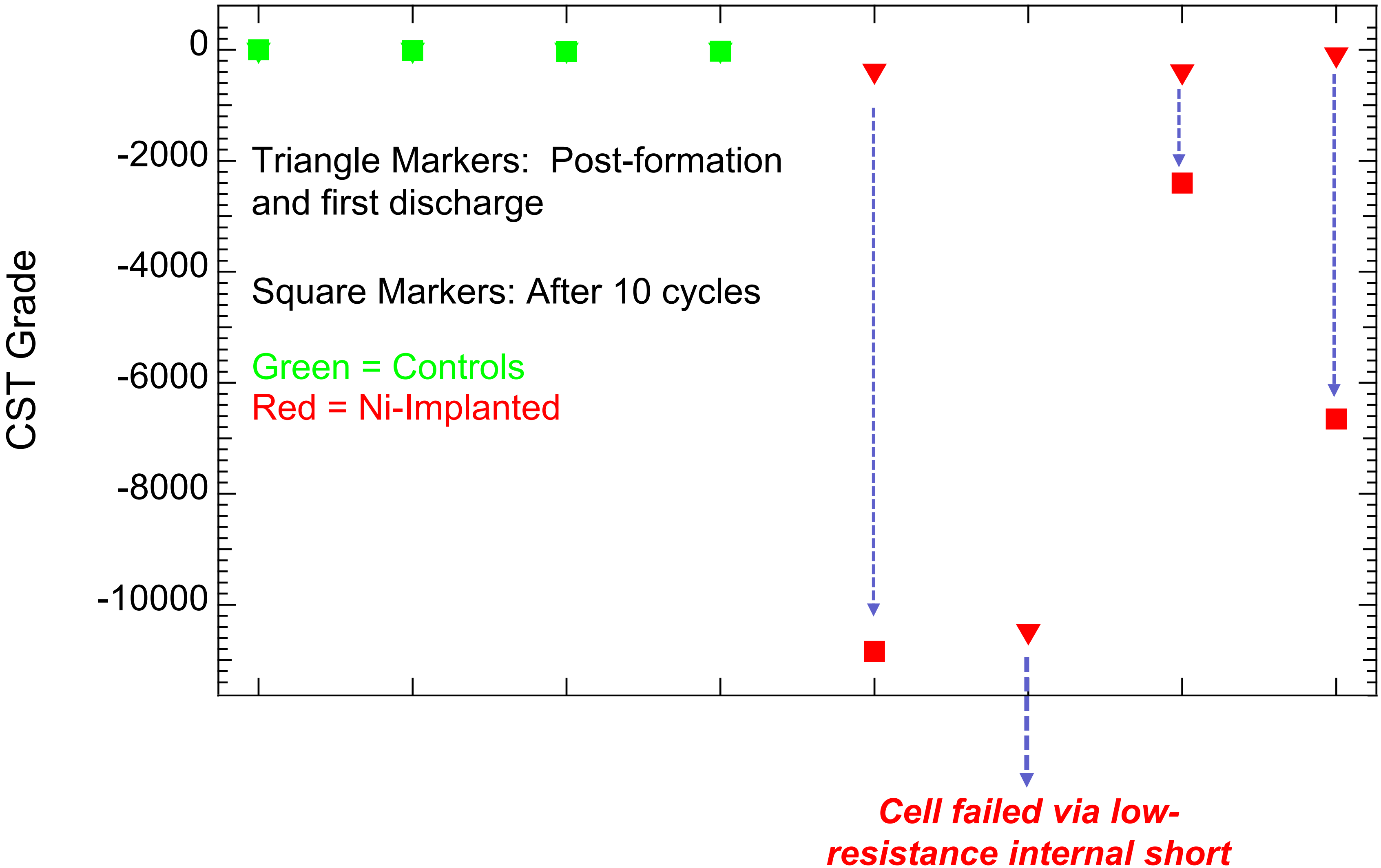
Some Examples of Results from Experimental Studies using Cells Implanted with Metal Particles

We show here CST data following formation charge then discharge to 30% SOC for four test articles implanted with 1mm Ni Particles and four controls.



➢ CST detected elevated self-discharge in all four of the Ni-implanted test articles.

Self-discharge severity in the particle-implanted cells grew over ten charge-discharge cycles as seen in the evolution of CST grades.



Summary

- CAMX Power has developed, implemented, and validated technology for rapid, high-sensitivity screening of Li-ion cells for elevated self-discharge.
- The sensitivity of CST, demonstrated to > 10MΩ, rapidly and effectively identifies elevated self-discharge in cells passed by manufacturer QC methodologies.
- CST enables 100% acceptance screening of cells by delivering the highest screening sensitivity to even minute soft shorts in just hours vs. months.
- Other CST applications include sample-based lot acceptance testing for incoming cells and comparative quality assessments of candidate cells and suppliers.
- Performance and efficacy of CST have been successfully established across different cell form factors (cylindrical, pouch) and full range of Li-ion chemistries.
- We have implemented and validated CST in multiple prototype instruments including our most recently completed 100-cell capacity CST Instrument.

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