CAMX Power High Sensitivity Cell Screening Technology: Recent Advancements and Results from Evaluations of Li-Ion Cell Populations

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Abstract: *CAMX Power has developed an ultra-high sensitivity Cell Screening Technology (CST) that has been demonstrated to rapidly detect anomalous self-discharge in lithium-ion (Li-ion) cells to sensitivities of 10MΩ or greater. CST has been implemented in multiple prototype instrument designs to-date that deliver multi-megaohm detection sensitivity in scans taking just hours versus months or even years to achieve the same sensitivities by typical long-term monitoring of cell Open Circuit Voltage (OCV). The throughput and sensitivity of CST enables efficient, cost-effective acceptance screening of Li-ion cells for self-discharge that would otherwise be impractical from cost and/or calendar time perspectives. We report results demonstrating capabilities of CST and for validation and performance benchmarking for our latest-generation, 100-cell capacity CST prototype instrument. We further present results for screening of populations of thousands of Li-ion cells.*

Keywords: Li-ion; acceptance screening; self-discharge; screening throughput; short detection; cell screening.

Introduction

Acceptance Testing of Li-Ion Cells: Background, Considerations, & Objectives

Acceptance testing of Li-ion cells comprises evaluating incoming cells against protocols and metrics selected and defined by the end-user to verify that the cells they will utilize conform to standards of safety, reliability, and/or performance selected by and controlled by the end user. While cell manufacturers carry out certain quality control testing on the cells they manufacture, the associated test protocols and pass/fail criteria are generally not made available to any but the most significant of their customers. It is only these exceptional, top-level customers that are granted access to quality control practices, procedures, and metrics and may further even have staff embedded in the cell manufacturing facilities as well as foreknowledge and approval authority over any changes to manufacturing and QC processes. For all other end-users of Li-ion cells, however, no such access is available and manufacturer QC is a relatively opaque process as are the specific QC protocols and pass/fail metrics employed, and any changes or modifications to those protocols over time.

The practice of acceptance screening gives the end-user full control of qualification protocols to which cells are subjected and full knowledge of the results of those qualification protocols. One of many key benefits of this level of control and knowledge of incoming cell screening metrics is that the end-user can have advance warning of unexpected changes to cell quality that may indicate cause for concern. Such advance warning, prior to any such cells being assembled into batteries, is a valuable tool to manage safety and reliability of Li-ion energy storage systems and can be of special importance where cells are sourced from third parties, rather than directly from the cell manufacturer, adding a layer of uncertainty regarding cell provenance.

While manufacturers generally test cells against, for example, specifications for minimum available capacity and may also test for basic impedance characteristics (e.g., 1kHz impedance), by far the most time-consuming quality control check – and the most crucial with respect to the safety of the cell - is evaluating cells for anomalous self-discharge. This process attempts to eliminate cells that may be developing internal short-circuits, a primary cause of violent failures of cells in the field, and typically comprises tracking cell Open Circuit Voltage (OCV) over a significant holding period (e.g., 14-days). This OCV tracking process dominates cell manufacturing cycle time and thus represents a significant cost to the manufacturer owing to the equipment, manufacturing floor space, and residence time associated with it. This cost is accepted as part of the cell manufacturing process because of the critical importance of reducing the likelihood that a cell with an incipient internal short circuit will enter service and cause a catastrophic failure (e.g., thermal runaway) in the field. However, OCV change over time is not a particularly sensitive means to measure self-discharge and therefore to achieve reasonable detection sensitivity lengthy hold periods are needed. Accordingly, manufacturers face a fundamental trade-off between the effectiveness of QC for detection of anomalous self-discharge, and the cost and time required by that process. There is a strong cost incentive for manufacturers to minimize the duration of the hold period for OCV monitoring even though it is recognized that the shorter the monitoring period, the lower the sensitivity for detection of anomalous self-discharge/soft shorts in cells. Thus, there are strong economic pressures on cell manufacturers to balance the cost of quality control against sensitivity and effectiveness of that quality control in identifying cells with anomalous self-discharge that may develop internal shorts. These economic pressures only mount further as manufacturers are driven to reduce Li-ion cell production costs.

To provide some perspective on how and why a cell with anomalous self-discharge can still pass manufacturer QC, we present some technical background on the process of testing cells for soft shorts/anomalous self-discharge via cell OCV monitoring over time. The data in Figure 1 shows test results for a set of cells for which OCV was tracked for 14 days. In this test, a set of cells was prepared that included cells with load resistances connected across the cell terminal, as surrogates for internal self-discharge processes, ranging in value from 5000 Ω to 1,000,000 Ω (this technique reproduces, with high electrical fidelity, the equivalent circuit comprised by an internal short forming an electronically conductive path between the positive and negative electrodes of a cell of a given resistance). The cell group also included cells without such surrogates. All cells had previously been screened (OCV monitoring for >6 months) to be free of any anomalous self-discharge. The test sequence we used simulates the protocol cells might see in manufacturer QC in which cells are brought to full charge after initial formation and capacity testing and then held for a period of time to measure level of OCV loss. Our test results illustrate how some levels of cell self-discharge are detectable by OCV tracking for a given period of time while others (of higher resistance) are not. As can be seen from the traces in Figure 1, cell OCV decline for self-discharge test resistances of 100,000 Ω or lower is distinct from the black (no self-discharge) control cells. However, at self-discharge resistances greater than 100,000Ω OCV changes are no longer sufficiently distinguishable from the responses of the normal (no self-discharge/black traces), allowing these cells to pass manufacturer QC despite having elevated self-discharge.

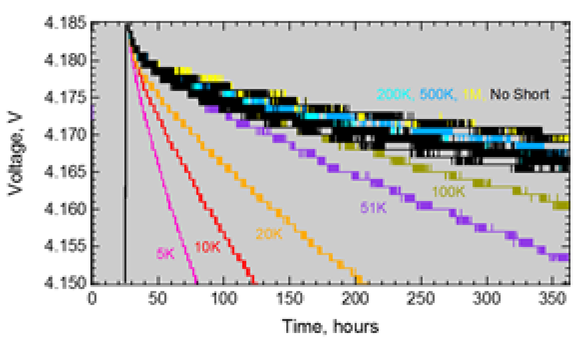

Figure 1. Example of results for common industry cell screening practice of long-term voltage monitoring. 2.6Ah 18650 cells were aged for 14 days after a formation-rate charge (C/20). Steps in the traces arise from the intrinsic resolution limit of the battery test equipment. Black traces show multiple cells with no simulated shorts, while other traces show cells with simulated shorts of the resistances indicated. Shorts from 5000 to 100,000 ohms were distinguishable from short-free cells over the 14-day monitoring period, while higher resistance shorts were not.

It should be noted that this test was conducted with commercially available cells that had already been formed (and screened by the manufacturer) prior to this test. This might, of course, tend to yield a *tighter* distribution in short-free cell voltage decay characteristics than would be expected in a population of newly formed cells (and thus our test may have yielded *higher* sensitivity than might actually be achieved with newly formed cells).

The CAMX Power Cell Screening Technology

The CAMX Power ultra-high sensitivity Cell Screening Technology (CST) employs electrical diagnostics developed specifically to measure and quantify self-discharge in Li-ion cells and to identify cells with anomalous levels of self-discharge (i.e., levels that are greater than normal background self-discharge levels typical for a cell of a given type). CST electrical diagnostics are intrinsically far more sensitive to the presence of internal shorts in cells than long-term monitoring of cell voltage. Figure 2 shows test data demonstrating the sensitivity and performance of our cell screening technology in the rapid detection of anomalous self-discharge even at high resistance levels.

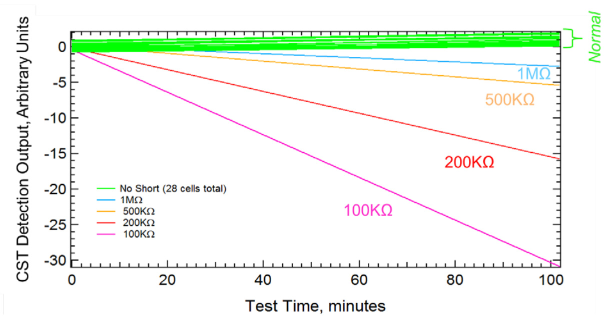

Figure 2. CST response for a group of 32 cells (2.6Ah 18650-format) with calibrated self-discharge levels introduced for four cells (load resistance as surrogates).

Data in Figure 2 shows that a self-discharge resistance of 100KΩ is readily detectable by CST in under an hour versus the many days required via existing industry practice of tracking OCV change over time (as shown in Figure 1).

Characterization of self-discharge resistance by CST is quantitative. Figure 3 shows the linear relationship between CST grade (the slope of the raw CST scan data) and conductance (1/resistance) of the self-discharge/soft-short resistance. Data of the type shown in Figure 3 provides a simple means to establish the quantitative relationship needed to translate CST grade to self-discharge resistance for a given cell type.

Accurate and effective identification of cells with anomalous self-discharge using CST has been extensively verified via independent confirmation using long-term tracking of cell OCVs following testing with CST. Without exception, cells identified by CST as showing elevated self-discharge have shown accelerated drop in OCV over time, confirming the CST findings.

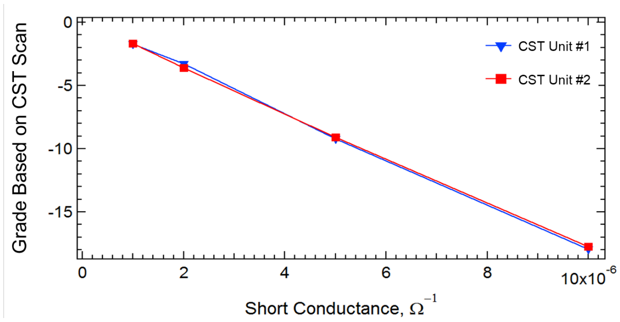

Figure 3. As shown here for two CST instruments tested, CST grade is linearly dependent on self-discharge conductance (1/resistance). Results shown are for self-discharge resistances of 1MΩ, 500KΩ, 200KΩ, and 100KΩ.

We have found that CST can detect and quantify self-discharge levels in excess of 10,000,000 ohms (10MΩ) under appropriate test conditions. We note that to fully realize the benefits of the CST diagnostic methodology, test conditions need to be regulated in certain respects to avoid factors that might cause measurement perturbation and/or drift. These factors include changing cell temperature and recent charge or discharge processes that create non-equilibrium cell conditions.

The ability of CST to identify cells with anomalous self-discharge/soft shorts not identified by manufacture QC is illustrated by the example in Figure 4. Here, CST testing showed that *10% of the cells* had elevated self-discharge. That these cells with elevated self-discharge were not identified by manufacturer QC is perhaps not surprising – in each case the levels of self-discharge were beyond our estimate of the limit of detection for OCV change over a 14-day hold period. This group of cells had been provided to us for construction of a battery module. We note that only cells from the group that passed CST (free of anomalous self-discharge) were utilized to construct that module. Cells that failed CST (elevated self-discharge) were rejected.

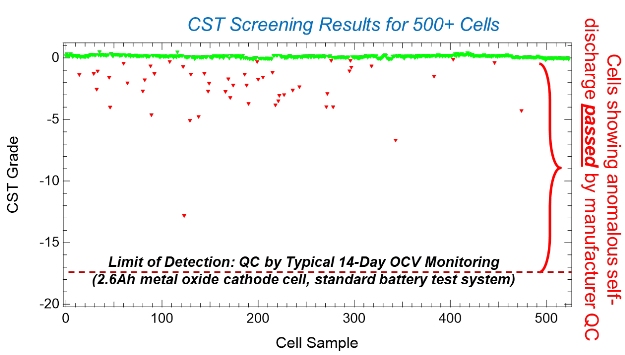

Figure 4. CST results for a group of > 500 commercially-available 18650 cells (leading manufacturer). Anomalous self-discharge was identified in 10% of the cells.

It is not typical in our experience to-date to find that 10% of a cell population has elevated self-discharge levels/soft shorts, so this finding was significant. We have now tested over 45,000 cells to-date using CST for DoD and Government clients. In each lot of cells tested, CST has identified cells with elevated self-discharge levels. Table 1 summarizes CST screening results for nine cell groups we have screened and number of cells failed from each group.

Table 1. CST Test Results for Tested Groups of 18650 Cells.

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

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

It is important to recognize that the presence of elevated self-discharge does not necessarily mean that a cell is unsafe. While there are many uncertainties associated with the appropriate level of concern that should be attributed to anomalous self-discharge in a cell, consideration of the root cause of self-discharge provides an important framework for understanding and evaluating risk. Anomalous self-discharge can be classified into two main categories as a function of the underlying mechanism that produces the self-discharge, as described in Figure 5.

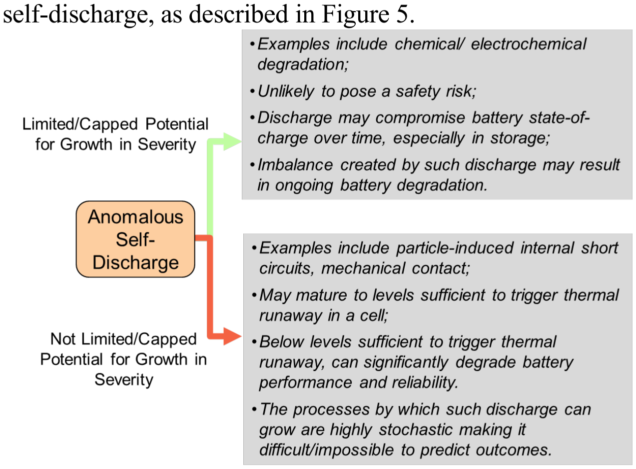

Figure 5. Root cause of elevated self-discharge provides important context for understanding and evaluating risk.

Prototype 100-Cell Capacity CST Instrument: Capabilities and Test Results

Our most recently implemented prototype CST instrument is a 100-cell capacity unit for 18650-format cells. A photograph is shown in Figure 6. The unit is designed to accept cells in the same 10x10 rectangular array configuration in which the cells are typically packaged for shipping. The instrument is powered via USB connection to a computer running the CST graphical user interface which provides all user operation, control, data logging, and CST instrument settings and parameter management functionalities.

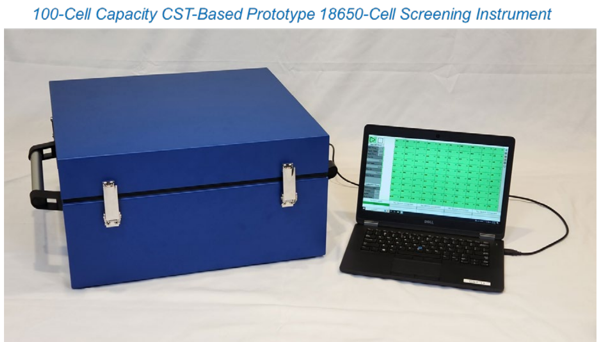

Figure 6. Photograph of our state-of-the-art prototype CST instrument. The laptop in the photograph is running the CST user interface.

Example test results (3.5Ah 18650 cells) using the 100-cell prototype CST instrument are shown in Figure 7. The CST instrument provides a surrogate self-discharge resistance functionality at four of the cell test positions which has been enabled during the test in Figure 7 at the resistance levels shown. This functionality can be used to obtain the cell-specific quantitative calibration data that is used to translate CST grade to self-discharge resistance using the linear relationship between self-discharge conductance and CST grade (as seen in the inset graph in Figure 7).

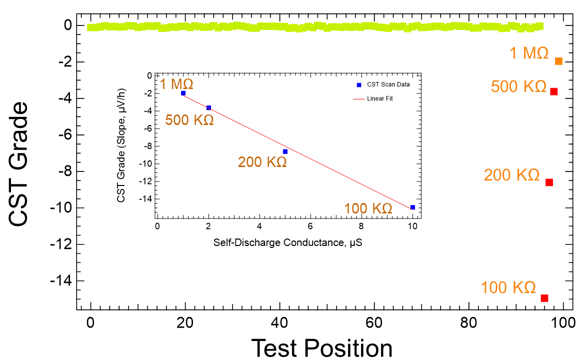

Figure 7. Test results using our 100-cell CST Instrument prototype for 3.5Ah 18650 cells from a major manufacturer. The self-discharge resistance surrogate functionality is enabled for the last four test positions in this run at the resistances noted.

CST can resolve differences in self-discharge between cells well into the multi-megohm range as demonstrated by the test data shown in Figure 8 which includes test resistances to 5MΩ. With respect to the maximum sensitivity that may be achievable using CST, the test data and detection thresholds shown in Figure 9 support achievable sensitivities of 10 MΩ or greater. As the results show, a cell with CST grade at the detection threshold for 10 MΩ is distinguishable and separated from the cluster of normal, anomalous self-discharge free cells (96 samples in total) discharge) and thus 10MΩ would be a detectable level.

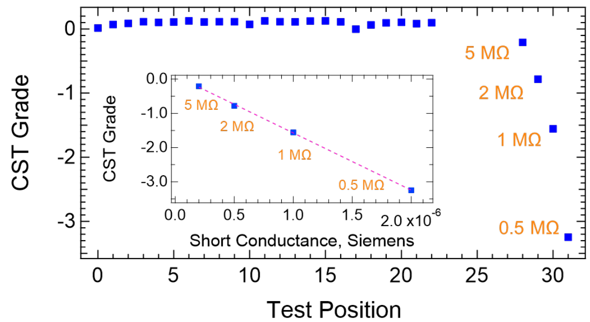

Figure 8. Test results demonstrating the ability of CST to resolve self-discharge resistances tested here to 5MΩ (2.6Ah 18650 cells).

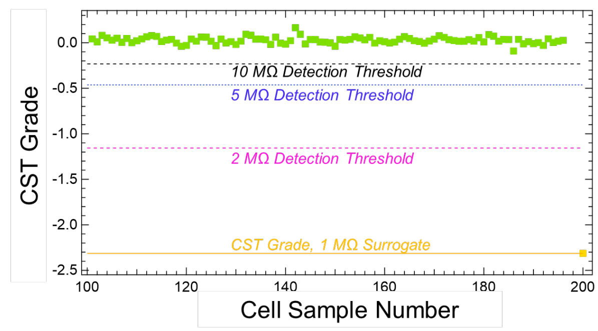

Figure 9. CST test data for 3.5Ah 18650 cells including one cell (bottom right of graph) with a 1 MΩ self-discharge surrogate enabled (load resistance across cell). Resistance detection thresholds were calculated from calibration data establishing the quantitative relationship between CST grade and self-discharge resistance (e.g., as described with respect to Figure 3).

In conclusion, CST delivers rapid, ultra-high sensitivity characterization of self-discharge in Li-ion cells. CST can be utilized for rapid acceptance screening of cells in a small fraction of the time that would be required using typical industry practice of OCV change over an extended holding period. CST discerns self-discharge in the multi-megaohm range in scans taking just hours. These capabilities have been validated and demonstrated in multiple prototypes including our most recently implemented 100-cell capacity prototype instrument, for which results have been presented here.

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