Accelerated Aging Test Method Incorporating Load Profiles for Primary Lithium Batteries in Active Implantable Medical Devices

User Manual

Tool Reference

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Accelerated Aging Test Method Incorporating Load Profiles for Primary Lithium Batteries in Active Implantable Medical Devices

User Manual v1.0

Overview of the document:

This Regulatory Science Tool (RST) provides an experimental protocol that may be used to help quantify battery degradation, specifically, capacity loss and internal resistance growth caused by high-energy therapeutic discharges typically seen in Active Implantable Medical Devices (AIMDs) such as implantable cardioverter defibrillators (ICDs). Unlike traditional heating-based calendar-aging methods (Appendix A), this protocol enables assessment of degradation from high current amplitude stress, a key aging driver in lithium systems such as $LiMnO_2$ (Example provided in Appendix B). The test protocol was informed by simulation results from an analytically derived computational model, which we developed to estimate battery aging and performance under realistic device load profiles (Appendix C). Users may use this model to simulate battery transient voltage, surface temperature, depth of discharge and internal resistance growth in response to user-provided electrical loads specific to their use case and to identify appropriate relaxation times (rest periods between pulses) for battery testing. The MATLAB and Python scripts we used for data analysis and visualization of our use case application are explained in detail in Appendix D.

OSEL GitHub page:

https://github.com/dbp-osel/AIMD-Batteries-Accelerated-Aging-Test-Method

Objective of pulse-induced accelerated aging test:

The purpose of this protocol is to characterize battery performance and degradation in the form of capacity loss and internal resistance growth in primary battery cells under application-relevant stress conditions. The procedure includes *baseline characterization*, *accelerated aging through high-energy pulse cycling*, and *post-aging assessment*. Key performance indicators such as internal resistance, capacity retention, and pulse energy response are used to quantify the impact of repeated high-load events on battery integrity.

This RST does not specify sample sizes or selection criteria. Users may choose their **sample size** and **selection criteria** based on their own application-specific requirements, statistical robustness, and available resources. The test method is designed to ensure controlled, repeatable testing conditions for meaningful comparison across cell batches, load profiles, and aging scenarios.

Protocol Overview: Step-by-Step Summary

This protocol consists of the following major steps:

1. **Battery Cell Selection and Preparation**
   Select a statistically representative sample of fresh cells based on open-circuit voltage (OCV) distribution and test requirements.
2. **Baseline Internal Resistance Measurement**
   Measure the initial internal resistance of selected cells using a standardized Direct Current Internal Resistance (DCIR) method.
3. **Baseline Capacity Measurement**
   Determine the full capacity of fresh cells using a constant current–constant voltage (CCCV) discharge test after a rest period following the DCIR experiment.
4. **High-Energy Pulse-Induced Aging Tests**
   Subject cells to repeated high-energy current pulses to simulate accelerated aging and stress conditions relevant to the application. The energy of these pulses is equivalent to the pulse energy required for charging the defibrillation capacitor in ICD applications.
5. **Post-Pulse Capacity and Internal Resistance Measurement**
   Measure the lost capacity and internal resistance growth of aged cells to evaluate degradation resulting from pulse-induced aging.
6. **Data Export and Consolidation for Analysis**
   Export recorded test data from the battery tester, consolidate files, and prepare the dataset for external analysis using provided Python and MATLAB scripts.

Materials

The following equipment and data are used in the model and test protocol:

- User-defined load profile of the battery during therapeutic events (e.g. a 30 J continuous discharge for charging the defibrillation capacitor, occurring at most once per month)

- Battery test equipment with suitable discharge rates and current amplitudes relevant to the user's specific batteries under evaluation. We used ARBIN LBT20084 for up to 200 mA discharges and an ARBIN BT2000 for up to 10 A discharge capabilities. Each battery test equipment comes with its own dedicated data visualization software. We used ARBIN Data Watcher to access recorded data.

- Heat chamber allowing temperature-controlled storage up to 60°C. We used an ARBIN MZTC chamber.

- Test data was analyzed using MATLAB 2022b and Thonny integrated development environment with built-in Python 3.10, and we installed Pandas library (version 2.3.1) in Thonny's packages. Computational models were run using MATLAB 2022b.

Pulse Induced Accelerated Aging Test Protocol:

Step 1: Battery Cell Selection and Preparation

Note: Users provide their own sample size and selection criteria as test protocol inputs based on their own application needs, statistical expectations, and available resources.

1.1 Acquire Test Cells
Obtain a batch of fresh primary cells appropriate for the intended application. If possible, select all cells from the same production lot to minimize manufacturing variability.

1.2 Stabilize and Measure OCV
Allow cells to stabilize at room temperature. Measure the open-circuit voltage (OCV) of each cell using a calibrated voltmeter. Record all values.

1.3 Determine OCV Distribution
Analyze the OCV data to determine the mean and standard deviation. Assume the OCVs follow a normal distribution, which is generally valid for well-controlled manufacturing processes.

1.4 Select Test Samples
From the full batch, select approximately 17 cells whose OCVs fall within a narrow range centered around the calculated mean (e.g., within ± 5% or ± 1 standard deviation). This helps ensure sample consistency and minimizes the impact of outliers.

1.5 Document Selection Criteria
Record the selected voltage range and rationale for your sample size. Adjust these parameters as needed based on your test objective, load profile, and resource constraints.

1.6 Assign Cells to Test Conditions
Distribute the selected cells across the different test conditions. For example, if testing multiple pulse amplitudes, assign three cells per condition to enable averaging and analysis of variance. Proceed to **Step 2**

Step 2: Baseline Internal Resistance Measurement

Objective:

To determine the baseline internal resistance of primary cells using the Direct Current Internal Resistance (DCIR) method.[1]

2.1 Sample Selection

Select two cells from the previously OCV-matched group for baseline measurement testing.

2.2 Equipment Setup

Mount the selected cells in a battery tester (e.g., ARBIN LBT20084 or equivalent). Verify all channels are calibrated and data logging is enabled.

[1] DCIR (Direct Current Internal Resistance) quantifies how much voltage a cell drops when a step current is applied. Based on Ohm's Law, DCIR reflects a cell's ability to deliver current efficiently and is calculated as the ratio of voltage drop to current change during short-duration current pulses. DCIR is a practical indicator of cell quality, aging, and performance under load.

2.3 DCIR Measurement Procedure

The values used in this step are for illustrative purposes. Users select parameter values based on their cell specifications and application requirements)

1. Pre-conditioning

- Discharge each cell at 50 mA for 40 minutes.

2. Voltage Ramp Preparation

- Apply a linear discharge current ramp at 20 µA/s for 35 minutes to gradually increase cell voltage in preparation for DCIR pulsing.

3. Dual Pulse DCIR Sequences

- Apply two square discharge current pulses of 200 mA amplitude and 2-second duration.
- Repeat this dual-pulse sequence four times, resulting in a total of eight DCIR pulses.
- Precede each sequence with:
  - 40 minutes of 50 mA constant current discharge, and
  - 35 minutes of ascending current ramp at 20 µA/s

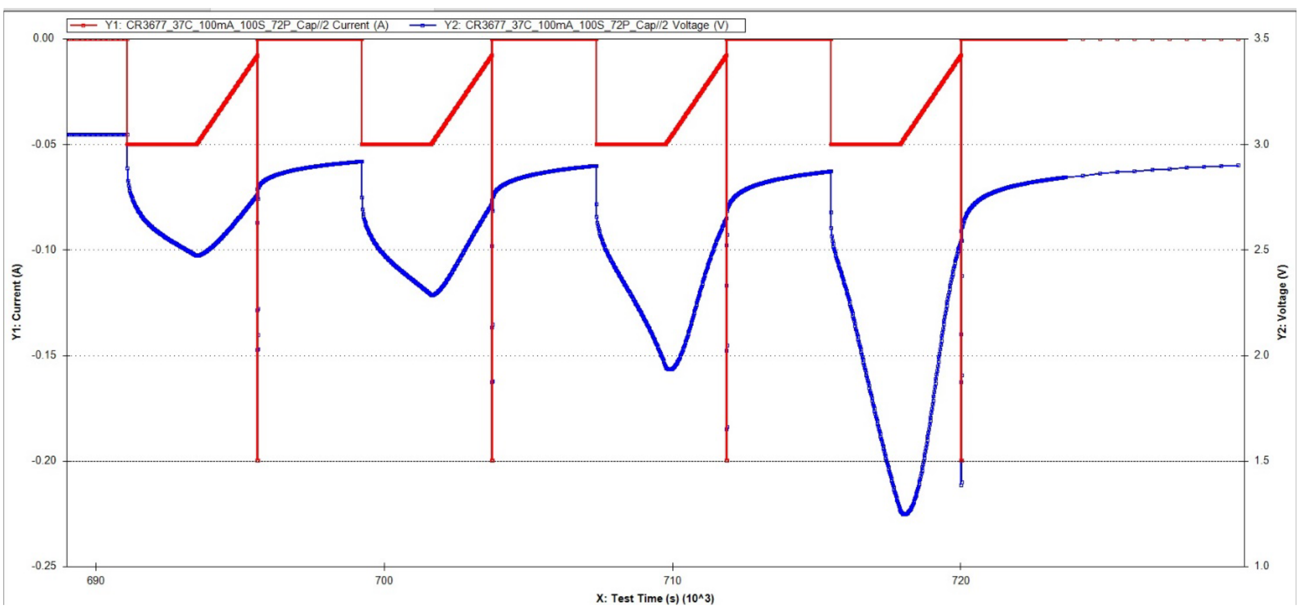

Figure (1) – Internal resistance measurement method

Figures in this document are generated by the ARBIN LBT20084 data watcher. In Figure (1) the raw data of voltage (blue) and current (red) are presented during the four dual-pulse DCIR experiment. Figure (2) shows a zoomed-in view of one of the 200 mA dual discharge pulses used for internal resistance measurement.

2.4 Voltage Drop and Resistance Calculation

1. Measure Voltage Drop (ΔV)

- Capture voltage immediately before the pulse (V_{start}) and at the end of the pulse (V_{end}).
- Compute: $\Delta V = V_{start} - V_{end}$

2. Define Current (ΔI)

- For a pulse from 0 mA to 200 mA: $\Delta \boldsymbol{I}$ = 200 mA

3. Calculate DCIR

- For each pulse number i: $DCIR_i = \frac{\Delta V_i}{\Delta I_i}$

4. Average Resistance

- Compute average across all 8 pulses: $IR_{avg} = \frac{1}{8}\sum_{i=1}^{i=8} DCIR_i$

1.1. 2.5 Data Documentation

Log all measured voltages, current pulses, and DCIR values.
Export time-series plots of voltage and current if available.
Record environmental conditions and test parameters.

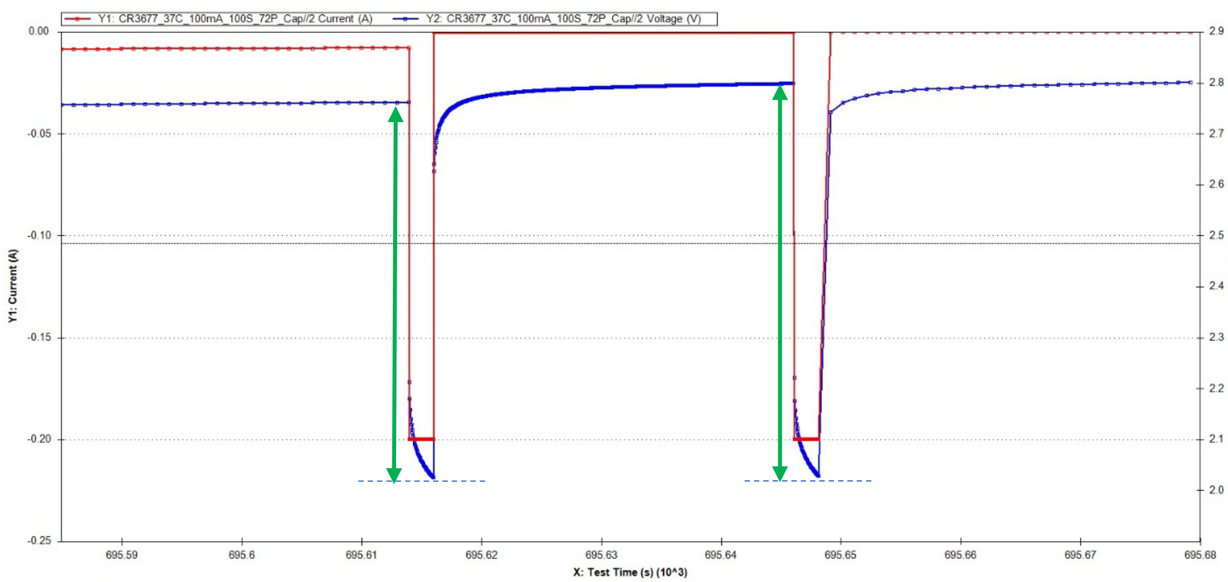

Figure (2) – The dual DCIR pulses - Voltage drops are shown by the two green arrows.

Step 3: Baseline Capacity Measurement

Objective:

To determine the baseline (100%) capacity of fresh cells using a constant current–constant voltage (CCCV) discharge method, following a rest period after internal resistance testing.

3.1 Post-Resistance Rest Period

After completing the DCIR test, allow the tested cells to rest for 48 hours at 37 °C without any electrical load. This rest period enables full voltage recovery and stabilization prior to capacity measurement, to minimize transient effects on degradation from previous tests.

3.2 Discharge Test Setup (The values in this test are fixed and should not be altered**)**

Conduct the capacity test using the CCCV discharge method.
Maintain the test environment at 37 °C to simulate elevated-temperature operating conditions.
Set the battery tester to discharge the cells at a C/50 constant current until the cell voltage reaches the cut-off voltage of 2.0 V.
Once the cut-off voltage is reached, switch to constant voltage mode, maintaining 2.0 V while allowing the discharge current to taper off.
Stop the test when the current drops below C/500, which serves as the cut-off current for this procedure.

Note: Refer to your battery tester's user manual (e.g., ARBIN, Neware, Maccor) for assistance with programming a CCCV discharge sequence.

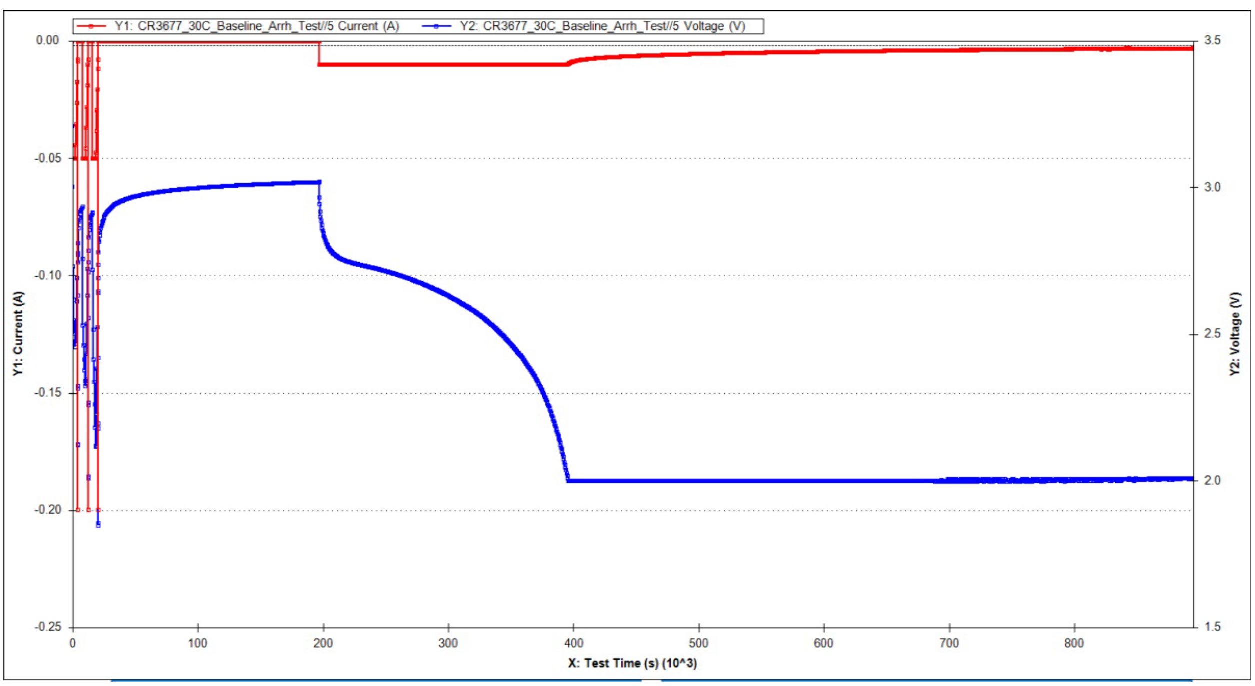

Figure (3) – DCIR, two-day rest, CCCV experiment

Figure (3) presents the data collected from both experiments (voltage data in blue and current data in red color). The two-day rest is for the cell voltage to recover and fully stabilized prior to cell capacity measurement. Figure (4) shows a zoomed-in view of the current and voltage data for CCCV capacity measurement test. (refer to user manual of your battery tester on how to conduct this experiment)

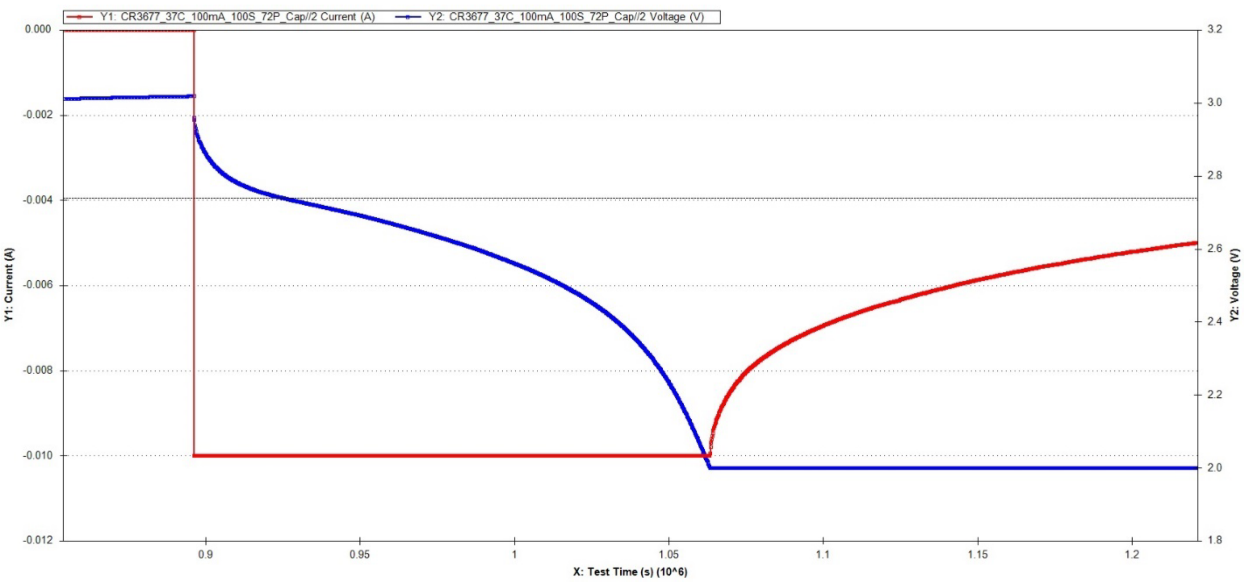

Figure (4) – CCCV experiment

3.3 Capacity Calculation

Measure the total capacity delivered from the start of the constant current discharge until the current falls below C/500 during the constant voltage phase.
This value is typically logged automatically by the battery tester and recorded in units of mAh or Ah.
Look for parameters labeled as "Discharge Capacity," "Q_discharge," or similar.
If needed, calculate manually by integrating the current over time:

$$Capacity\ (Ah) = \int_0^t I(t)\ dt$$

Where: $I(t)$ = discharge current as a function of time

The resulting capacity is recorded as the 100% baseline capacity for that specific cell and is used for benchmarking future degradation or cycling results.

3.4 Data Documentation

Record and export the following data:
- Total discharged capacity (mAh or Ah)
- Discharge current and voltage vs. time curves
- Test temperature and equipment settings
- Cut-off voltage and cut-off current values

Step 4: High-Energy Pulse-Induced Aging Tests

Table (1):

<table>
<tr><th colspan="3">Group</th><th>Sub-group</th><th>Current [mA]</th><th>Pulse width [Seconds]</th><th>Cell voltage [volts]</th><th>Pulse energy [Joules]</th><th>Number of pulses</th></tr>
<tr><td rowspan="5">1</td><td rowspan="5">2</td><td rowspan="5">3</td><td>1</td><td>50</td><td>200</td><td>3 – 3.2</td><td>30 – 32</td><td>72</td></tr>
<tr><td>2</td><td>100</td><td>100</td><td>3 – 3.2</td><td>30 – 32</td><td>72</td></tr>
<tr><td>3</td><td>200</td><td>50</td><td>3 – 3.2</td><td>30 – 32</td><td>72</td></tr>
<tr><td>4</td><td>300</td><td>33</td><td>3 – 3.2</td><td>30 – 32</td><td>72</td></tr>
<tr><td>5</td><td>400</td><td>25</td><td>3 – 3.2</td><td>30 – 32</td><td>72</td></tr>
</table>

Objective:
To simulate accelerated aging of primary cells through repeated high-energy discharge pulses representative of field-use conditions. This step evaluates the effect of different pulse amplitudes on capacity degradation and internal resistance growth. The goal is to quantify how pulse-induced electrical stress impacts the long-term performance and longevity of the cells in their intended application.

4.1 Cell Grouping and Experimental Setup (the values in this test shown in Table (1) are picked by user to be appropriate with their cell specifications and statistical criteria requirement)

- Divide the remaining 15 test cells into three groups of five.
- Each group undergoes a pulse-induced aging protocol across five different pulse amplitude and duration combinations.
- Each pulse condition is tested with three replicate cells to ensure statistical reliability.

Note: Choose pulse profiles to reflect realistic energy delivery demands (e.g., high-rate pulses for defibrillation, industrial bursts, or consumer power surges). Ensure pulse energy, duration, and cell limits are compatible with the chosen pulse profile.

4.2 Sample Selection

- For each sub-group, select two cells with similar open-circuit voltages (OCVs) to ensure uniform initial conditions across samples.

4.3 Pulse Discharge Procedure

- Using a battery tester, discharge each cell under the designated pulse current and duration at 37 °C to replicate body core temperature in implantable applications.
- Set each pulse to deliver a defined amount of energy (e.g., ~30–32 J), relevant to your application.
- Adjust current and duration to remain within safe cell operating limits and to achieve the target energy delivery.

Note: Select test parameters corresponding to the particular battery chemistry and end-use device.

4.4 Post-Pulse Rest Period

- After each pulse, allow the cell to rest for a defined duration (e.g., 2 hours) to enable voltage relaxation and minimize thermal accumulation.

4.5 Pulse-Repetition Aging Cycle

- Repeat the pulse–rest cycle for each cell a total of 72 times, or per your accelerated aging design.
- This sequence is intended to simulate multi-year use, based on estimated pulse frequency (e.g., monthly or weekly discharge events).

4.6 Post-Aging Rest Period

- After completing all pulses, allow the cell to rest for 48 hours (or a suitable stabilization period) to enable voltage recovery before further analysis.

4.7 Repeat for All Sub-Groups

- Repeat steps 4.2 through 4.6 for all sub-groups representing different pulse conditions.
- Repeat the entire protocol for the remaining two test groups to ensure consistent results across batches.

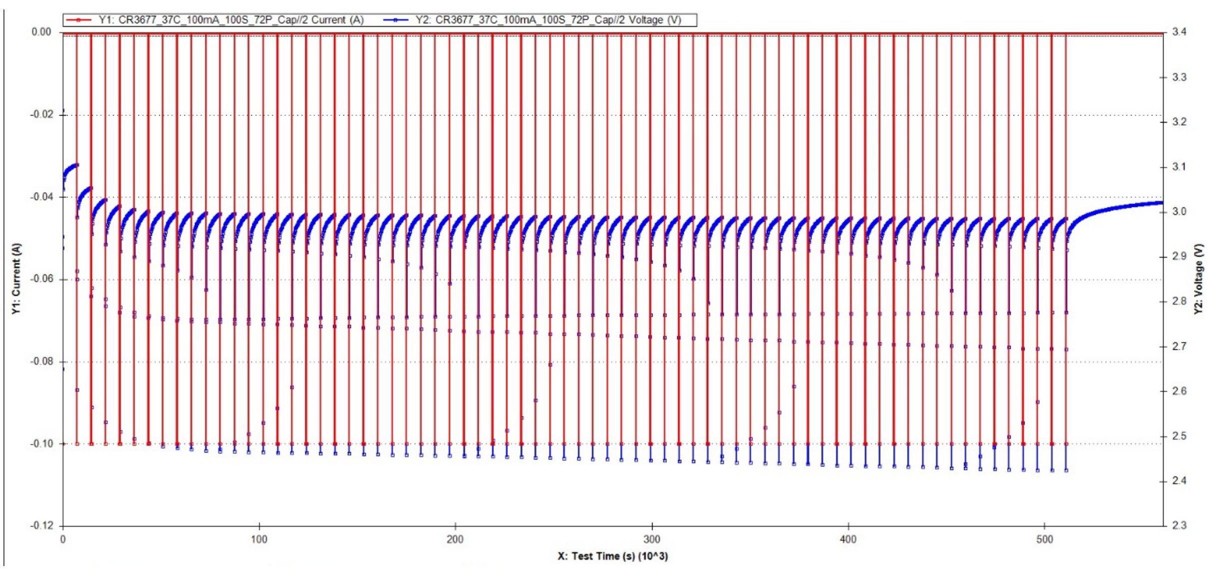

Figure (5) – 72 defibrillation pulses all applied in ~150 hours

Figure (5) is the recorded raw data of voltage (blue) and current (red) for this test, generated by ARBIN Data Watcher. Figure (6) shows a zoomed-in view of one of the defibrillation pulses.

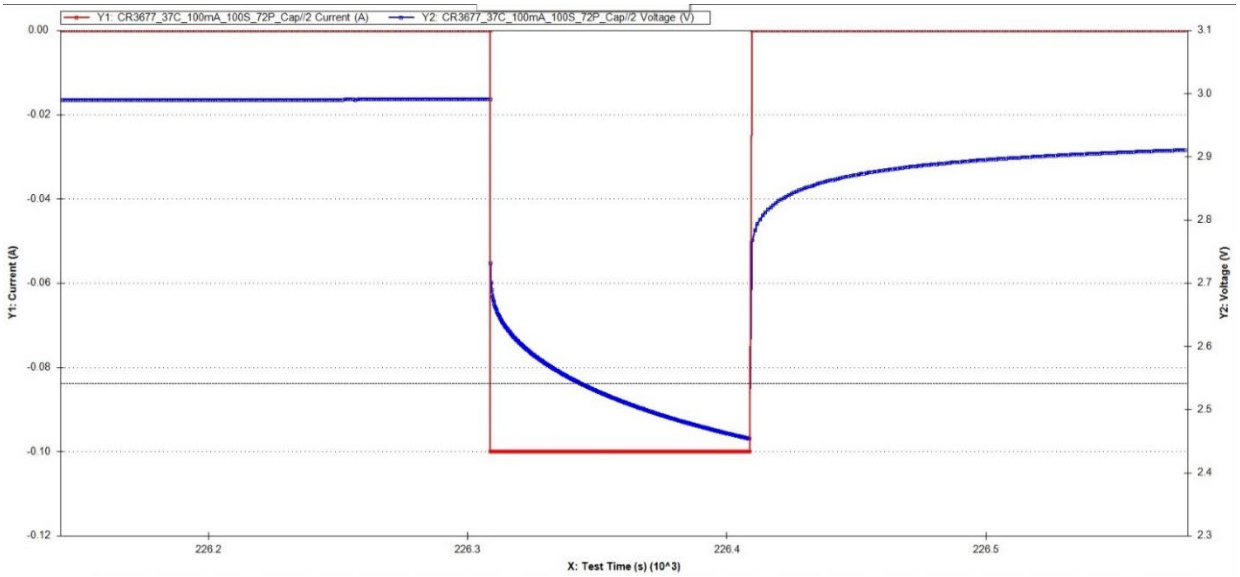

Figure (6) – A single defibrillation pulse

Step 5: Post-Pulse Capacity and Internal Resistance Measurement

5.1 Measurement of Aged Cells

Using the same methods outlined in Step 2 and Step 3, measure the internal resistance and remaining capacity of all 15 aged cells across all groups.

5.2 Total Available Capacity Calculation

For each cell, determine the total available capacity by summing:
- The capacity delivered during the 72 pulse discharges
- The remaining capacity measured via CCCV discharge

This total represents the available capacity of the aged cell.

5.3 Capacity Loss Calculation

Subtract the baseline (fresh cell) capacity measured in Step 3 from the total available capacity calculated in Step 5.2. This difference indicates the capacity loss due to high-energy pulse-induced aging.

5.4 Expressing Capacity Loss

Express the capacity loss as a percentage of the fresh cell capacity:

$$\%\ Capacity\ loss = \frac{[Fresh\ cell\ capacity - Aged\ cell\ calapcity]}{Fresh\ cell\ capacity} \times 100$$

This percentage reflects the cumulative degradation due to repeated high-energy pulse exposure and quantifies performance impact across pulse amplitudes.

APPENDIX A

Elevated-temperature aging protocol for calendar-life estimation of primary lithium batteries

The Arrhenius method is a commonly applied scientific approach for estimating the calendar-life degradation of batteries by modeling the temperature dependence of capacity fade using first-order reaction kinetics [1-3]. This method assumes that the rate of capacity loss follows an exponential dependence on temperature, consistent with the Arrhenius equation, where the degradation process is treated as a thermally activated reaction [4]. This approach enables accelerated aging studies by subjecting cells to elevated temperatures and extracting reaction rate constants that can be extrapolated to predict long-term performance at different temperature conditions. In this appendix, we detail the application of the Arrhenius framework to our specific use case involving primary $LiMnO_2$ batteries for AIMDs, including experimental procedures, model fitting, and projection techniques. This traditional approach may complement results from the previously described pulsed load profile test method.

<u>Prerequisites for implementing the Arrhenius temperature-induced accelerated aging test:</u>

The following equipment and data were used:

- Battery test equipment. We used ARBIN LBT20084 for up to 200mA discharge capability.
- Heat chamber for thermal storage up to 60°C. We used ARBIN MZTC chamber.
- Prior knowledge and expertise with operating the battery test equipment.
- Test data was analyzed using MATLAB 2022b and Thonny integrated development environment with built-in Python 3.10, and we installed Pandas library (version 2.3.1) in Thonny's packages. Computational models were run using MATLAB 2022b.

<u>Step 1: Initial battery selection and OCV measurement</u>

1.1- Battery Acquisition: Obtain a batch of fresh primary batteries (at least 11 cells) used in your application. We used Murata CR3677 lithium manganese dioxide ($LiMnO_2$) with a nominal capacity of 2Ah. These off-the-shelf cells feature similar chemistry and capacity characteristics to those used in active implantable medical devices (AIMDs).

1.2- OCV Screening: Measure the open-circuit voltage (OCV) of each battery and select 11 cells with OCVs within 3 – 3.2 volts range to minimize variability in initial state. This ensures that all selected cells are at a comparable starting condition to provide a consistent baseline for subsequent aging experiments.

<u>Step 2: Baseline internal resistance and capacity measurement</u>

2.1- Select 2 cells from each batch with similar OCV values.

2.2- Apply the four dual-pulse DCIR test (similar to page 2 -Step 2 of this document) to measure battery internal resistance.

2.3- Discharge one of the cells at 37°C using the CCCV constant current of C/50 until the cut-off voltage of 2.0 volts is reached. Once the voltage reaches 2.0 volts, switch to constant voltage mode and continue the discharge until the current drops below C/200. Measure the total discharged capacity and internal resistance of the cell.

2.4- Repeat the same procedure for the second cell, but at room temperature (24°C). This provides a baseline for capacity and internal resistance under non-accelerated conditions.

At the end of this step, the baseline capacity and internal resistance values at both 37°C and 24°C are established for fresh cells.

Step 3: Battery allocation for temperature aging

3.1- Allocate the remaining 9 fresh cells into three temperature-specific groups, with 3 cells in each group:

Table (1):

group	Number of cells per group	Chamber temperature	duration	Intermittent removal for week 2, 4 and 6 measurements
1	3	37°C	6 weeks	One cell every two weeks
2	3	45°C	6 weeks	One cell every two weeks
3	3	50°C	6 weeks	One cell every two weeks

Step 4: High-temperature aging

4.1- Place each group of cells in separate temperature-controlled chambers set to their respective temperatures (37°C, 45°C, and 50°C). Allow the cells to age continuously under no-load conditions for a total duration of 6 weeks.

Step 5: Periodic testing during aging

5.1- Bi-Weekly Testing: Every 2 weeks, remove one cell from each chamber for testing.

5.2- Apply the four dual-pulse DCIR test (similar to page 2 -Step 2 of this document) to measure battery internal resistance.

5.3- Discharge the cells using the CCCV constant current of C/50 at their respective aging temperatures until the cut-off voltage of 2.0 volts is reached, then switch to constant voltage mode and continue the discharge until the current drops below C/200.

5.4- Record the total discharged capacity and internal resistance for each tested cell.

Step 6: Final data collection

6.1- At the end of 6 weeks, repeat the DCIR-CCCV discharge procedure for the final remaining cell in each group. Measure and record the total capacity and internal resistance to capture the final degradation state of the cells.

6.2- By the end of the test, each temperature group will have three data points (initial aging, mid-point aging, and final aging) for analysis of the degradation trend as a function of both temperature and time.

Step 7: Data analysis: Applying Arrhenius equation to the measured aging parameters (Capacity loss/Internal resistance growth)

2. Arrhenius-Based Aging Factor

The Arrhenius equation parameters, including the activation energy and the pre-exponential factor, are typically determined by fitting experimental data.
Traditionally, the Arrhenius equation is employed with data from batteries exposed to specific temperatures over set time periods under constant loads simulating idle device conditions. In this approach, battery degradation is primarily connected to temperature, similar to reliability testing for semiconductors or pharmaceuticals. However, this method does not account for load-induced stress, mechanical strain, or electrical cycling factors that significantly impact real-world battery performance.

Illustration of Calculating Arrhenius Coefficients ($\boldsymbol{E_a}$and A)

a) The Arrhenius Equation is expressed as:

$k = Ae^{\frac{-E_a}{RT}}$ (Eq.1)

Where:
k is the rate constant (aging rate),
A is the pre-exponential factor (constant for a given reaction),
E_a is the activation energy (eV) for the aging process,
R is the gas constant (8.314J×mol^{-1}e.K^{-1}),
T is the absolute temperature (in Kelvin).

b) Transform the equation for linearization to calculate the parameters E_a and A of the Arrhenius equation. Taking the natural logarithm on both sides:

$ln(k) = ln(A) - \frac{E_a}{R}.\frac{1}{T}$ (Eq.2)

This is now a straight-line equation:

$y = mx + c$ (Eq.3)

Where:

$y = Ln(k)$ (Eq.4)

$x = \frac{1}{T}$ (Eq.5)

$$m = -\frac{E_a}{R} \text{ (Eq.6)}$$

$$c = \ln(A) \text{ (Eq.7)}$$

MATLAB code for implementing the Arrhenius-based temperature-induced capacity degradation for calendar-life prediction of primary lithium cells is provided with this RST.

The following two MATLAB files are for reading and analyzing Arrhenius experiment data imported from ARBIN:

- CR3677_37C_45C_50C_W_2_4_6.mat
- CR3677_37C_45C_50C_W_2_4_6.m

For Arrhenius model fitting, the following code performs parameter identification and projects capacity fade over time based on the experimentally observed capacity loss data and analysis presented above

- CR3677_Arrhenius_Analysis_Week_2_4_6.m

CR3677 batteries aged for 2 weeks at 37 °C, 45 °C, and 50 °C

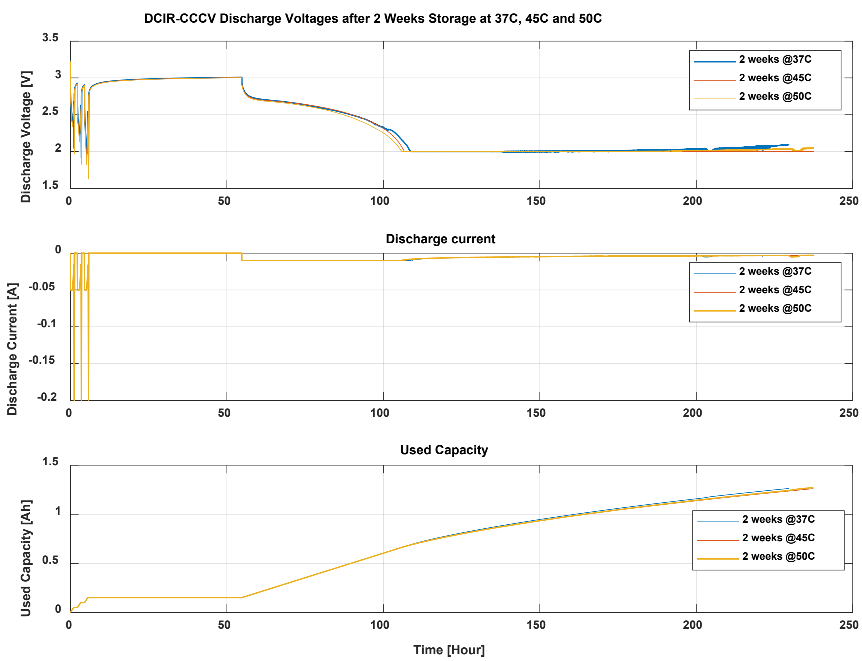

Figure (1) – Three cells aged for 2 weeks at 37C, 45C and 50C are under DCIR-CCCV experiment for internal resistance and capacity loss measurement

Week 2 analysis of temperature-driven battery aging parameters:

Table (2):

Cells (CR3677)	Storage temperature	Storage time	Discharge test temperature	CCCV discharge protocol	Used/Discharged Capacity at the end of the test [Ah]	Available Capacity [%]	Capacity loss [mAh]	Capacity loss [%]	Initial internal resistance
Cell#0	Fresh cell	Fresh cell	Room temperature (24C)	Cut-off voltage: 2.00 V Cut-off current: 4 mA	1.4829 [Ah]	100 %	0 [mAh]	0	4 [Ω]
Cell #1	37 C	2 weeks	Room temperature (24C)	Cut-off voltage: 2.00 V Cut-off current: 4 mA	1.157 [Ah]	78.02 %	325.9 [mAh]	21.98 %	4.89 [Ω]
Cell#2	45 C	2 weeks	Room temperature (24C)	Cut-off voltage: 2.00 V Cut-off current: 4 mA	1.141 [Ah]	76.94 %	341.9 [mAh]	23.06 %	5.16 [Ω]
Cell#3	50 C	2 weeks	Room temperature (24C)	Cut-off voltage: 2.00 V Cut-off current: 4 mA	1.137 [Ah]	76.67 %	345.9 [mAh]	23.33 %	5.08 [Ω]

CR3677 batteries aged for 4 weeks at 37 °C, 45 °C, and 50 °C

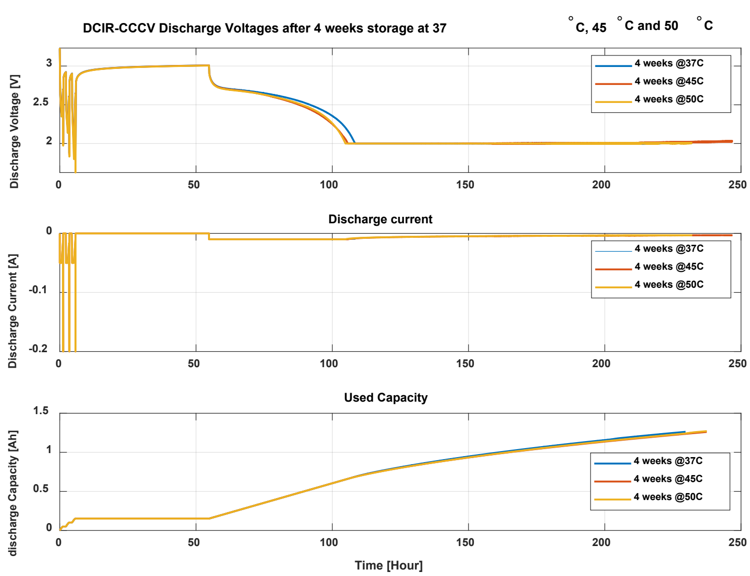

Figure (2) – Three cells aged for 4 weeks at 37C, 45C and 50C are under DCIR-CCCV experiment for internal resistance and capacity loss measurement

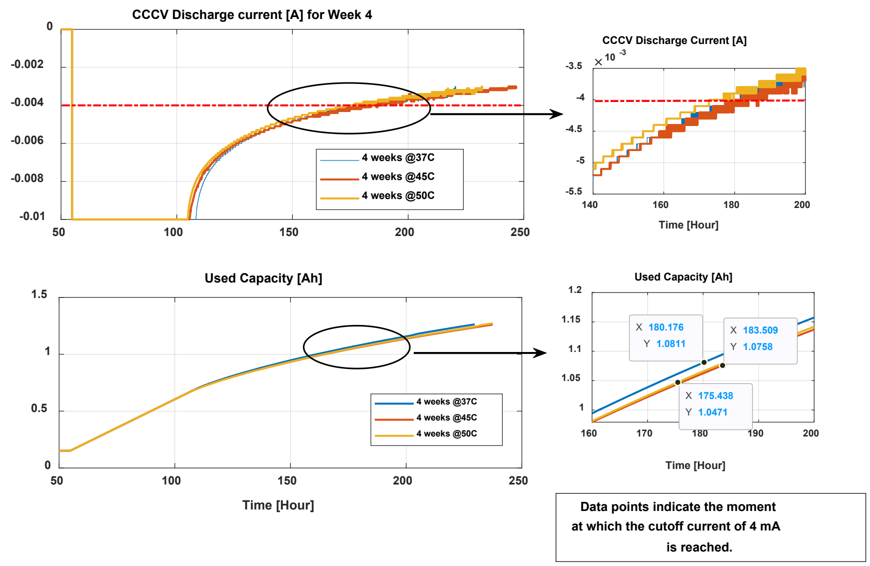

Figure (3) – Zoomed-in at the end of the CCCV experiment for capacity loss measurement for week-4 data

Week 4 analysis of temperature-driven battery aging parameters:

Table (3):

Cells (CR3677)	Storage temperature	Storage time	Discharge test temperature	CCCV discharge protocol	Used/Discharged Capacity at the end of the test [Ah]	Available Capacity [%]	Capacity loss [mAh]	Capacity loss [%]	Initial internal resistance
Cell#0	Fresh cell	Fresh cell	Room temperature (24C)	Cut-off voltage: 2.00 V Cut-off current: 4 mA	1.4829 [Ah]	100 %	0	0	4 [Ω]
Cell #4	37C	4 weeks	Room temperature (24C)	Cut-off voltage: 2.00 V Cut-off current: 3 mA	1.081 [Ah]	72.89 %	401.90 [mAh]	27.1 %	5.03 [Ω]
Cell#5	45C	4 weeks	Room temperature (24C)	Cut-off voltage: 2.00 V Cut-off current: 4 mA	1.075 [Ah]	72.49 %	407.9 [mAh]	27.50 %	5.07 [Ω]

Cell#6	**50C**	**4 weeks**	**Room temperature (24C)**	**Cut-off voltage: 2.00 V Cut-off current: 4 mA**	**1.047 [Ah]**	**70.60 %**	**435.9 [mAh]**	**29.39 %**	**5.12 [Ω]**

CR3677 batteries aged for 6 weeks at 37 °C, 45 °C, and 50 °C

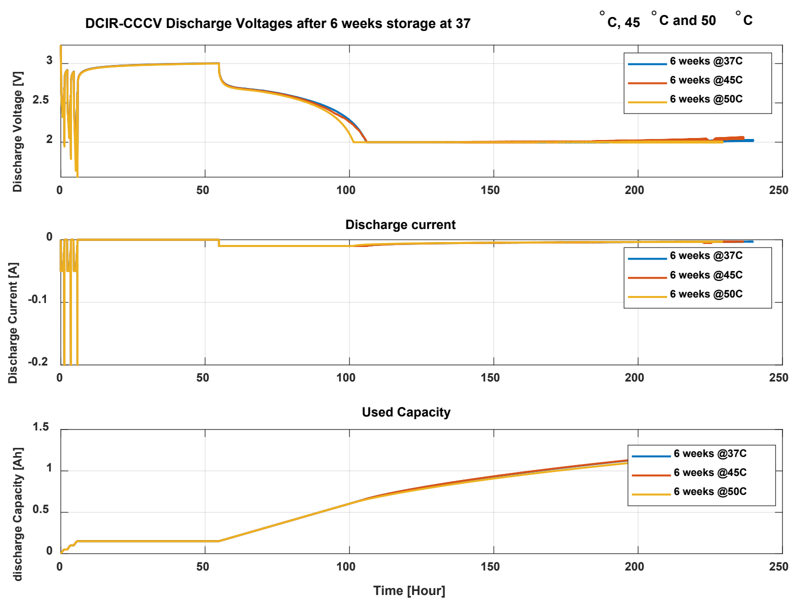

Figure (4) – Three cells aged for 6 weeks at 37C, 45C and 50C are under DCIR-CCCV experiment for internal resistance and capacity loss measurement

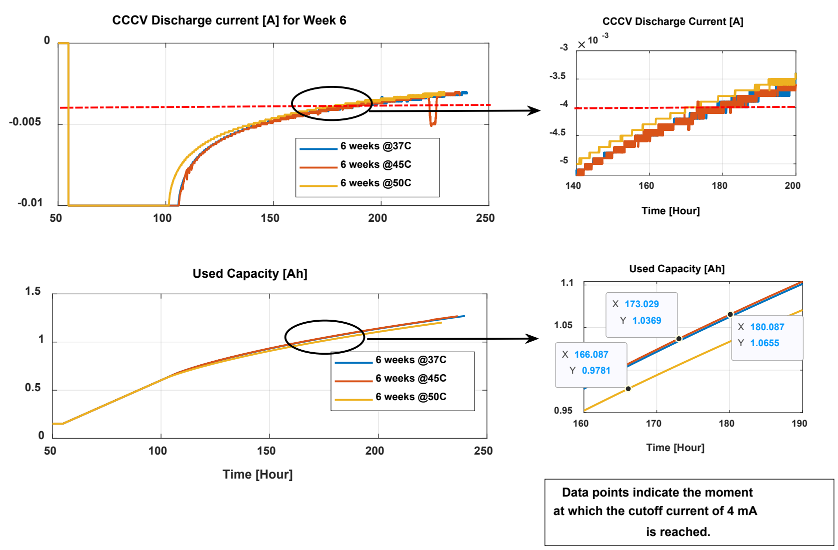

Figure (5) – Zoomed-in at the end of the CCCV experiment for capacity loss measurement for week-6 data

Week 6 analysis of temperature-driven battery aging parameters:

Table (4):

Cells (CR3677)	Storage temperature	Storage time	Discharge test temperature	CCCV discharge protocol	Used/Discharged Capacity at the end of the test [Ah]	Available Capacity [%]	Capacity loss [mAh]	Capacity loss [%]	Initial internal resistance
Cell#0	**Fresh cell**	**Fresh cell**	**Room temperature (24C)**	**Cut-off voltage: 2.00 V Cut-off current: 4 mA**	**1.4829 [Ah]**	**100 %**	**0 [mAh]**	**0**	**4 [Ω]**
Cell #7	**37C**	**6 weeks**	**Room temperature (24C)**	**Cut-off voltage: 2.00 V Cut-off current: 4 mA**	**1.065 [Ah]**	**71.81%**	**417.9 [mAh]**	**28.18 %**	**5.13 [Ω]**
Cell#8	**45C**	**6 weeks**	**Room temperature (24C)**	**Cut-off voltage: 2.00 V Cut-off current: 4 mA**	**1.036 [Ah]**	**69.86 %**	**446.9 [mAh]**	**30.13 %**	**5.11 [Ω]**
Cell#9	**50C**	**6 weeks**	**Room temperature (24C)**	**Cut-off voltage: 2.00 V Cut-off current: 4 mA**	**0.978 [Ah]**	**65.95 %**	**504.9 [mAh]**	**34.04 %**	**5.27 [Ω]**

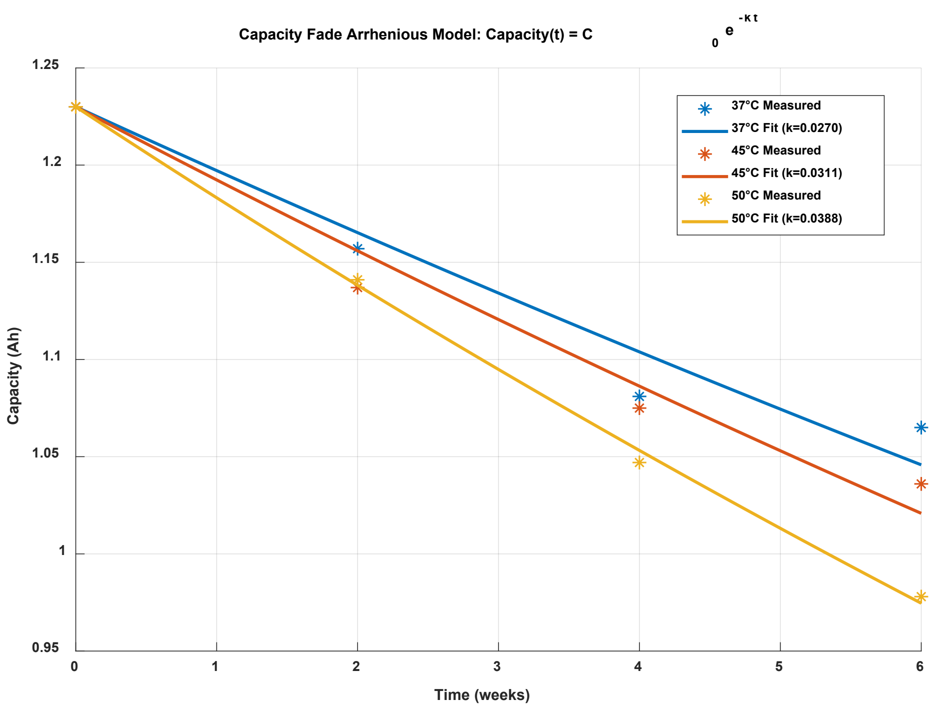

Figure (7) – Plotting the measured retained capacity versus storage time at 37C, 45C and 50C to fit the first order degradation model and obtain the capacity fade rate as the aging factor "k"

Longevity analysis based on aged cell's capacity of the temperature-induced accelerated aging experiment:

Table (5):

Storage duration / Storage temperature	2 weeks	4 weeks	6 weeks	Capacity fade rate	Arrhenius Parameters:
37° C	1.157 [Ah]	1.081 [Ah]	1.065 [Ah]	$K_{37°C} = 0.027$	$E_a = 22224.62 \frac{J}{mol.k}$ $A = 147\ mAh$
45° C	1.137 [Ah]	1.075 [Ah]	1.036 [Ah]	$K_{45°C} = 0.0311$	
50° C	1.141 [Ah]	1.047 [Ah]	0.978 [Ah]	$K_{50°C} = 0.0388$	

x = Capacity

$$\frac{d}{dt}x = x \times k, \quad where\ k\ is\ the\ rate\ of\ change\ of\ capacity\ assuming\ that\ it\ follows\ the\ first-order\ kinetiks$$

$$\rightarrow x(t) = x_0 e^{-k.t}$$

$$k\ is\ obtained\ using\ Arrhenius\ equation: k = A \times e^{-\frac{E_a}{RT}}$$

x_0: *Capacity of a fresh cell*

A: *pre − exponential factor*

E_a: *activation energy*

T: *storage temperature in Kelvin,*

R: *Universal gas constant* $= 8.314\ \frac{J}{mol.k}$

t: *time*

In Figure 7, the measured retained capacities of cells stored at 37 °C, 45 °C, and 50 °C are plotted over a 6-week period and fitted using an exponential decay model $x(t) = x_0 e^{-kt}$, where $x(t)$ is the first-order capacity dynamic and k is the capacity fade rate. The extracted rates are presented in the table (5), showing an expected increase in degradation rate with higher temperatures.

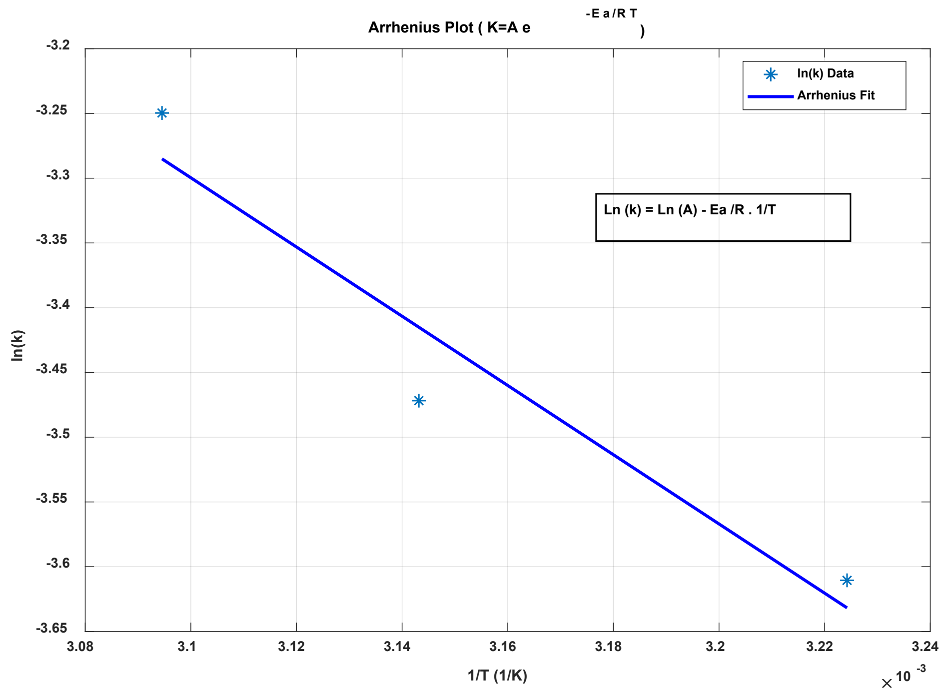

Figure (8) – Plotting the natural log of the calculated capacity fade rate vesrsus 1/temperature in kelvin to find the Arrhenius parameter activation energy (E_a) and pre-exponential factor (A) for projection of capacity fade over time for varios storage temperatures

Figure (8) uses these k values to construct an Arrhenius plot, plotting $\ln(k)$against $1/T$ (inverse temperature in Kelvin). The linear fit yields the activation energy $E_a = 22224.62 \frac{J}{mol.k}$ and the pre-exponential factor A $= 147$ mAh. These Arrhenius parameters allow extrapolation of the fade rate for other storage temperatures, which enables lifetime prediction under different thermal conditions as we did in Figure (9).

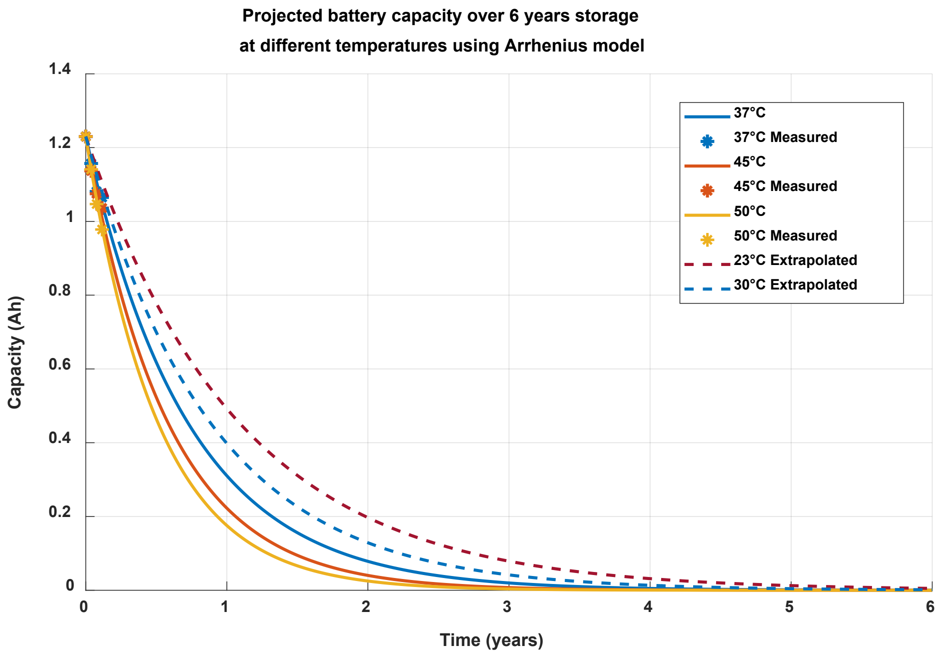

Figure (9) – Projected battery capacity at 23°C and 30°C, derived using first-order Arrhenius kinetics and assuming constant degradation rates per storage temperature

Assuming a constant capacity fade rate at each defined storage temperature and first-order kinetics for temperature-dependent degradation, one can solve for the activation energy (Ea) and pre-exponential factor (A) as we did in steps above. This enables calculation of the capacity fade rate constant (k) at different temperatures (e.g., 23°C and 30°C as shown in the Figure (9), which it provides an estimate of the cell's calendar life. Figure (9) shows the projected capacity fade of the cells over two years using the Arrhenius model. Solid lines represent an extrapolated first order exponential fit on the measured capacity loss at 37°C, 45°C, and 50°C, while dashed lines show projected Arrhenius results for 23°C and 30°C. As expected, higher storage temperatures lead to faster degradation. This model allows estimation of long-term calendar life under normal use conditions based on short-term accelerated aging data.

Figures (10) and (11) illustrate the effect of storage temperature and time on internal resistance (IR) growth of the cells during high-temperature storage. In Figure (10), internal resistance generally increases with rising storage temperature, especially by week 6, where a steep increase is observed at 50°C. This trend supports the thermally accelerated degradation hypothesis, as elevated temperatures promote electrolyte decomposition and SEI thickening, which contribute to resistance growth. Figure (11) shows how internal resistance evolves over time at fixed storage temperatures. IR increases steadily with storage duration at 37°C and 50°C, while at 45°C a slight initial dip is observed before a subsequent rise. Together, these figures confirm that both higher temperatures and longer storage durations may significantly contribute to internal resistance growth, a critical degradation parameter for battery performance in long-life applications like AIMDs.

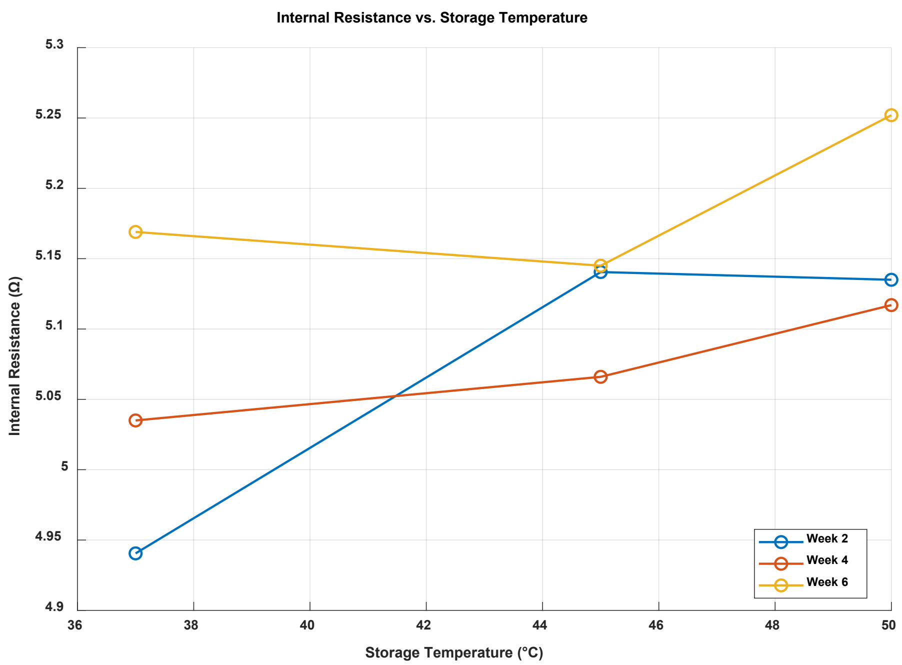

Figure (10) – IR vs storage temperature

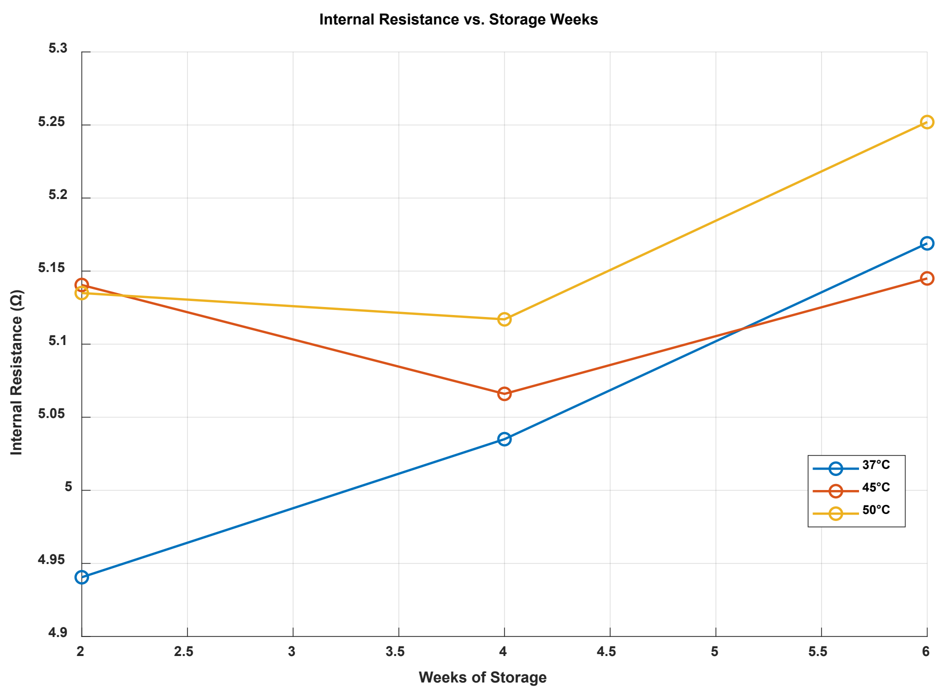

Figure (11) – IR vs weeks of storage

Reference:

1) Lam, Vivek N., Xiaofan Cui, Florian Stroebl, Maitri Uppaluri, Simona Onori, and William C. Chueh. "A decade of insights: Delving into calendar aging trends and implications." *Joule* 9, no. 1 (2025).

2) Gewald, Tanja, Markus Lienkamp, Dirk Lehmkuhl, and Alexander Hahn. "Accelerated aging characterization of lithium-ion cells: limitation of arrhenius dependency." In *2019 Fourteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, pp. 1-10. IEEE, 2019.

3) Wang, Ruixi, Xing Zhou, Yu Wang, Yukang Xiao, Zhichao Shi, Yajie Liu, and Tao Zhang. "Degradation analysis of lithium-ion batteries under ultrahigh-rate discharge profile." *Applied Energy* 376 (2024): 124241.

4) Edge, Jacqueline S., Simon O'Kane, Ryan Prosser, Niall D. Kirkaldy, Anisha N. Patel, Alastair Hales, Abir Ghosh et al. "Lithium ion battery degradation: what you need to know." *Physical Chemistry Chemical Physics* 23, no. 14 (2021): 8200-8221.

APPENDIX B:

Instruction for Running the MATLAB Code for the Aging-Coupled Thermo-Electrical Simulation model for Predicting Aging of Lithium Manganese Dioxide Primary Batteries in Implantable Medical Devices

Overview of the simulation model:

This MATLAB-based simulation tool, **Accelerated_Aging_TECM_Model_LiMnO2_Pulse_001.m**, models the thermo-electrical dynamics and aging of primary lithium manganese dioxide (LiMnO2) batteries used in Active Implantable Medical Devices (AIMDs). The model estimates battery terminal voltage, depth of discharge (DOD), battery surface temperature, and internal resistance growth over time under both continuous and pulsed loads, simulating real ICD usage scenarios. This code may assist pre-implantation assessment of cell performance and longevity with simulation under realistic device loads and environment.

Details of the model, its simulation results and model validation against experimental data are presented in the following publication:

An Arrhenius-Based Simulation Tool for Predicting Aging of Lithium Manganese Dioxide Primary Batteries in Implantable Medical Devices

MATLAB files used to run Arrhenius-based Aging-Coupled Thermo-Electrical Simulation modeling tool:

- Accelerated_Aging_TECM_Model_LiMnO2_Pulse_001.m
- Th.m
- DOD_OCV_Curve_LiMnO2.mat

Prerequisites:

MATLAB Installation: Ensure that MATLAB is installed on your system to run the code. This model is developed with MATLAB 2022b and is being tested with higher versions too.

Required data files: DOD_OCV_Curve_LiMnO2.mat, th.mat

Core Features:

- Internal resistance is the aging factor in this tool, which is modeled with Arrhenius-type kinetics.
- Simulates constant housekeeping loads and periodic defibrillation pulses at environment temperature
- Adjustable input current and temperature levels, thermal constants, and pulse configurations

Model States & Outputs:

- **x1**: State of Charge (SOC)
- **x2**: RC transient voltage
- **x3**: Battery surface temperature
- **x4**: Battery internal resistance
- **y**: Terminal voltage output

Adjustable Parameters:

- Q: Battery capacity (default 1200 mAh)
- initSOC: Initial state of charge (default 0.95)
- u: Housekeeping current (default -25 uA)
- u_shock: Pulse current (default -1 A)
- pulse_width_sec: Pulse duration in seconds (default 10s)
- interval_between_shocks_sec: Rest time between pulses (default 30s)
- Device_LifeTime: Simulation length in years (default 5)

Key Variables (th.mat):

- th(1,1): 1/(Battery Capacity in As)
- th(1,2): 1/RC constant
- th(1,3-1,4): Thermal exchange coefficients
- th(1,5): Scaling for transient voltage impact

Execution Steps:

1. Place the following files in the same directory:
   - Accelerated_Aging_TECM_Model_LiMnO2_Pulse_001.m,
   - DOD_OCV_Curve_LiMnO2.mat
   - th.mat
2. Open and run the .m file in MATLAB.
3. Review the terminal voltage, DOD, temperature, and resistance growth plots.

Simulation Logic Summary:

- Initializes time vector for the desired device life.
- Defines current profile with continuous and pulse loads.
- Applies Forward Euler method to solve thermal-electrical aging equations.
- Implements nonlinear growth model for ohmic resistance R2.
- Halts simulation when SOC < 1% or voltage drops below critical level.

Model Outputs (Visualized):

- Terminal voltage vs time
- Depth of Discharge (DOD) vs time
- Battery temperature vs time
- Resistance R2 and its rate change over time
- Characteristic OCV vs SOC curve

Customizing Simulations: Users can adjust SOC, currents, pulse settings, and temperature to evaluate performance under varied scenarios, keeping parameters within the ranges specified in the .m file. Sensitivity analysis can also be conducted by changing rate coefficients (a_R2, b_R2, etc.) to observe resistance aging impact.

Limitations:

- **Simplified Equivalent Circuit:** The model uses a single RC pair in the equivalent circuit, which limits its ability to capture complex transient behaviors. Accuracy could potentially be improved by incorporating multiple RC pairs to better represent electrochemical processes such as charge transfer and diffusion effects, but this would be outside the scope of this RST.
- **Fixed Thermal Parameters:** The thermal parameters used in the model (e.g., heat transfer coefficients and specific heat capacity) are assumed to be constant. In real batteries, these parameters may vary with aging, temperature, or depth of discharge, which could affect the model's accuracy in dynamic conditions.
- **Assumed Constant Ambient Temperature:** The model assumes a constant ambient temperature of 37°C to represent body conditions. However, implantable devices may experience temperature fluctuations due to physiological or environmental changes, which this model does not account for.
- **No Self-Discharge Effect:** The model does not account for long-term self-discharge that can gradually reduce capacity, especially over multi-year operation. These effects may be non-negligible in long-life medical devices.
- **Static OCV-DOD Relationship:** The OCV-DOD curve is assumed to remain unchanged over the battery's lifetime. In practice, aging and chemical degradation can alter the open-circuit voltage profile, potentially introducing errors in SOC and terminal voltage estimation over time.

APPENDIX C:

Analyzing the results for five cells in Group 1, under accelerated pulse-induced aging experiments

Five CR3677 batteries in accelerated pulse-induced aging at 37C:

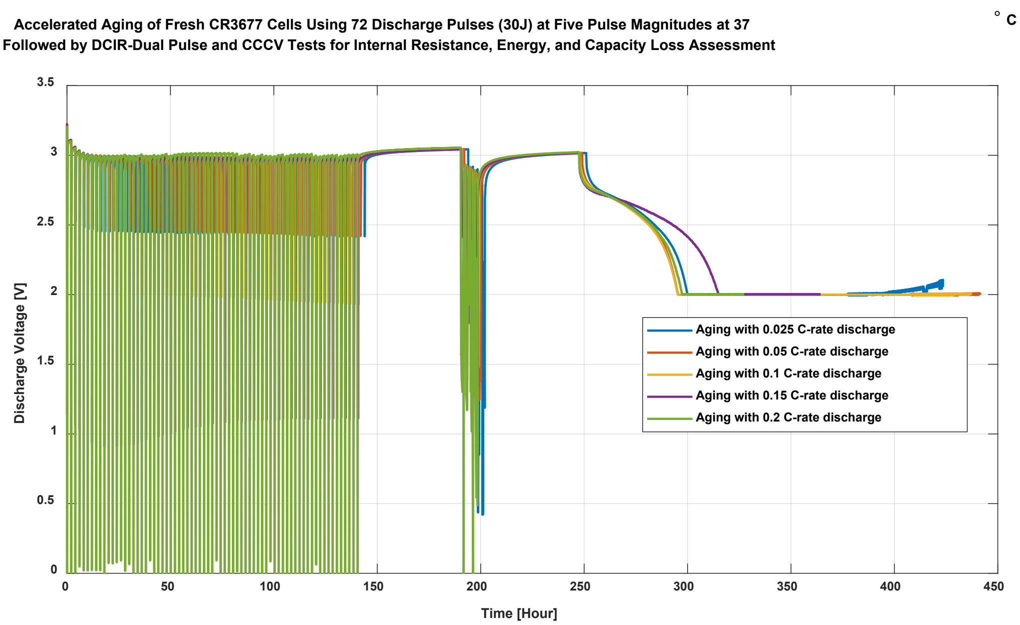

Figure (1)

Figures (1-3) illustrate the pulse-induced accelerated aging experiment on primary lithium cells subjected to 72 high-energy defibrillation pulses (30 J each) across five different C-rate magnitudes (from 0.025 C to 0.2 C). Figure (1) shows the discharge voltage profile. The first section (0–150 h) depicts repeated pulse discharges that simulate accelerated defibrillation events, followed by rest, four dual-pulse DCIR testing, and a CCCV discharge. As pulse amplitude increases from 0.025 C (or 50 mA in this case) to 0.2 C (or 400m mA), final discharge voltage curves show more deviation, indicating higher capacity loss and internal resistance buildup for higher C-rates.

Figure (2) displays the corresponding discharge current profiles. The initial block shows 72 discrete pulse currents, consistent across pulse groups, while the final CCCV phase highlights the cutoff behavior. The inset zooms into the final discharge region, emphasizing the defined 4 mA cutoff current for capacity determination, with earlier cutoff for more degraded cells.

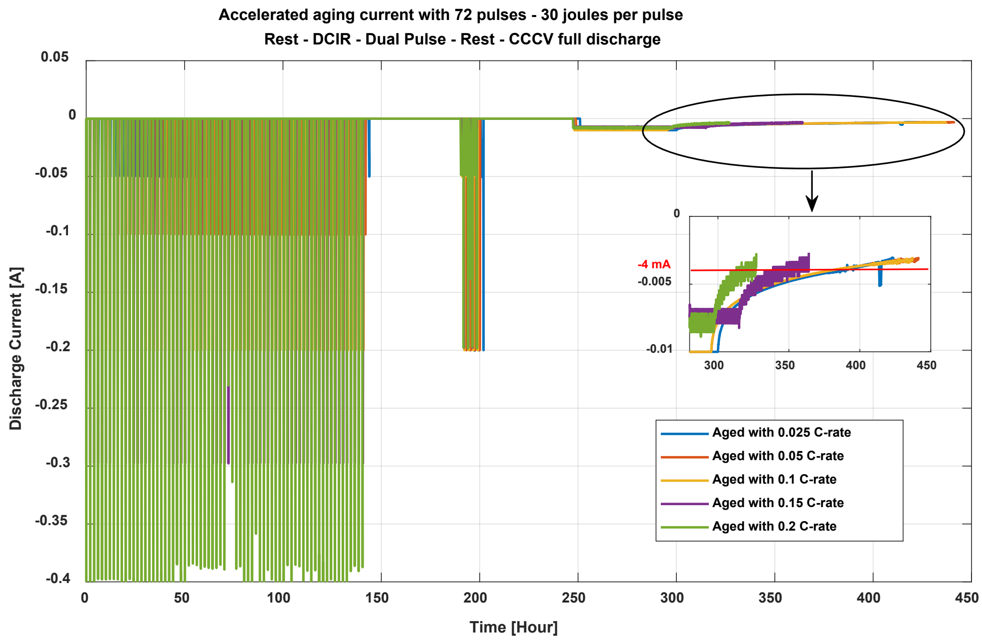

Figure (2)

Figure (3) presents the used capacity vs. time after CCCV discharge for each pulse-aged group. As expected, cells exposed to higher pulse magnitudes exhibit lower final capacities and reach the cutoff earlier. This confirms greater capacity degradation with increasing pulse stress.

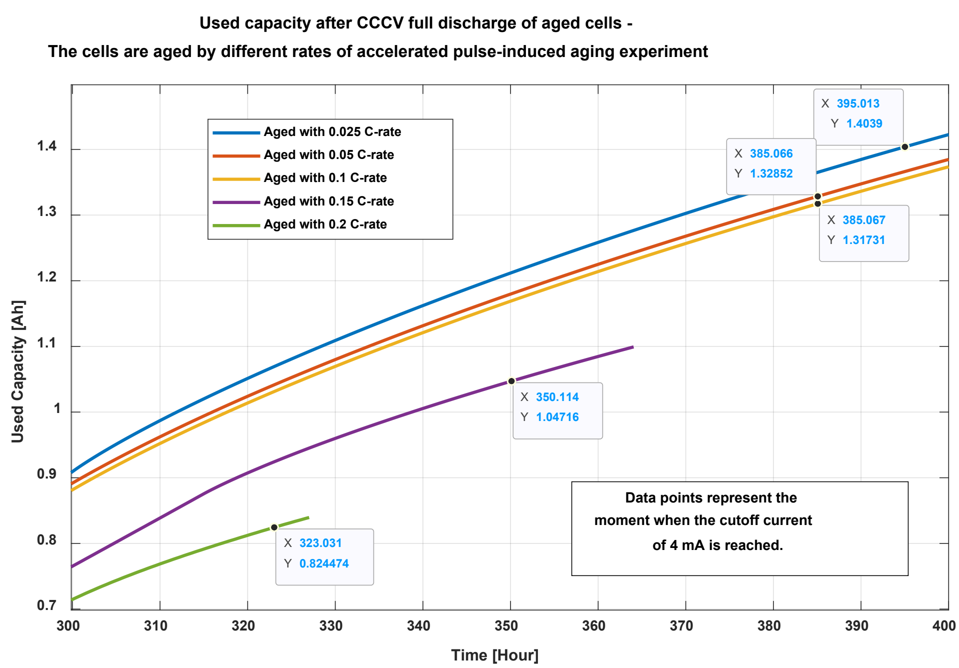

Figure (3)

To quantify degradation, the fresh cell's available capacity was measured to be 1.4829 Ah using a DCIR-CCCV test. The capacity used for the 72-pulse sequence is equivalent to 0.2 Ah, meaning 1.2829 Ah remains in an ideal, undegraded cell. After aging, the total measured capacity (Q_m) is lower than expected, indicating that some capacity was lost due to pulse-induced damage. Below is the step-by-step explanation of the calculations for identifying lost capacity in each aged cell:

Measured available capacity of fresh cell without pulse aging for a DCIR - CCCV test: 1.4829 Ah

Therefore, 100% capacity of CR3677 is 1.4829 [Ah]

Calculating the required capacity for 72 defibrillation pulse discharge where each pulse pulls 30 Joules out of a fully charged cell at 3-3.2 volts:

Q_0 = Available capacity of a fresh CR3677 cell for DCIR-CCCV measurement experiment: 1.4829 Ah

Q_{dp}= Required capacity for 72 defibrillation pulses at 30 Joules = 72*100mA*100 S = 720 As = 0.2 Ah

Q_r = Remaining capacity of a fresh cell, assuming zero capacity loss after defibrillation:

$Q_r = Q_0 - Q_{DP}$ = 1.2829 [Ah]

Q_m = Total delivered capacity, measured after pulse-induced aging experiment (high energy defibrillation + remaining capacity measurement test)

$\boldsymbol{Q_{lost} = Q_r - (Q_m - Q_{dp})}$, $\boldsymbol{Q_r, Q_{dp}}$ ***are constants,*** $\boldsymbol{Q_m}$ ***is measured for each pulse − induced aging experiment***.

If there is no loss of capacity during high energy defibrillation pulsation, then:

$$Q_r = Q_m - Q_{dp} \rightarrow Q_m = Q_0$$

But we observed that as the pulse amplitude increases (keeping the delivered capacity constant during DP), the $Q_m \neq Q_0$, therefore part of the available capacity is lost due to cell degradation caused by high energy pulsation.

$$Q_{lost-C_1} = 1.2829 - (1.403 - 0.2) = 0.079\ [Ah]$$

$$Q_{lost-C_2} = 1.2829 - (1.328 - 0.2) = 0.154\ [Ah]$$

$$Q_{lost-C_3} = 1.2829 - (1.317 - 0.2) = 0.165\ [Ah]$$

$$Q_{lost-C_4} = 1.2829 - (1.047 - 0.2) = 0.435\ [Ah]$$

$$Q_{lost-C_5} = 1.2829 - (0.824 - 0.2) = 0.658\ [Ah]$$

Capacity loss in percentage:

$$Q_{lost\%} = \frac{Q_{lost}}{Q_0} \times 10$$

Cell degradation parameters for batch 1 of pulse-induced accelerated aging:

Table (1):

Cells (CR3677)	test temperature	Pulse Amplitude	Pulse Width	CCCV discharge protocol	Total used/delivered Capacity Q_m [Ah]	Available Capacity [%]	Capacity loss Q_{lost} [Ah]	Capacity loss [%] $Q_{lost\%}$	Initial internal resistance
Cell#0 Fresh cell	**37C**	**N/A**	**N/A**	**Cut-off voltage: 2.00 V Cut-off current: 4 mA**	**1.4829 [Ah]**	**100 %**	**0**	**0**	**4 Ω**
Cell #1	**37C**	**50 mA**	**200 [Sec]**	**same**	**1.403 [Ah]**	**94.61 %**	**0.079**	**5.32 %**	**4.76 Ω**
Cell#2	**37C**	**100 mA**	**100 [Sec]**	**same**	**1.328 [Ah]**	**89.55%**	**0.154**	**10.38 %**	**4.8 Ω**
Cell#3	**37C**	**200 mA**	**50 [Sec]**	**same**	**1.317 [Ah]**	**88.81 %**	**0.165**	**11.12 %**	**4.61 Ω**
Cell#4	**37C**	**300 mA**	**33 [Sec]**	**same**	**1.047 [Ah]**	**70.60 %**	**0.435**	**29.33 %**	**5.28 Ω**
Cell#5	**37C**	**400 mA**	**25 [Sec]**	**same**	**0.824 [Ah]**	**55.57 %**	**0.658**	**44.37 %**	**9.3 Ω**

Plot the above results for capacity loss and internal resistance vs pulse amplitude for 5 cells:

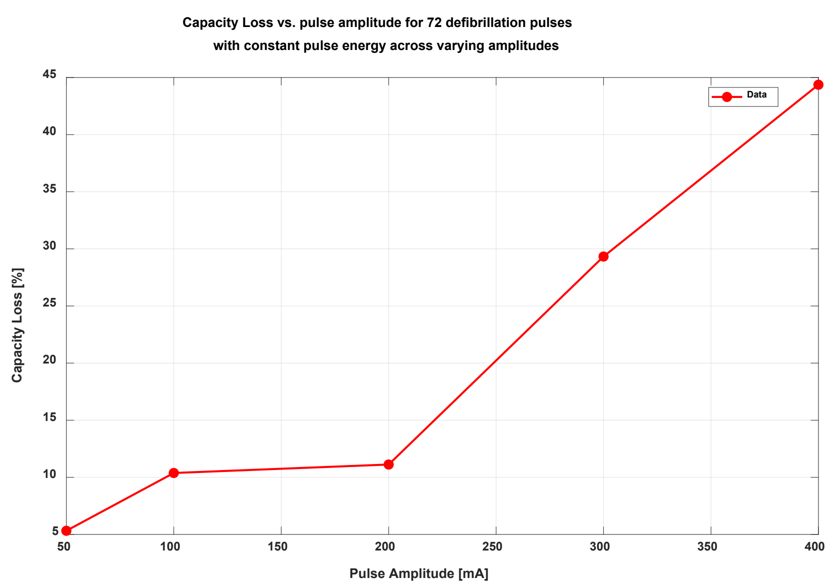

Figure (4)

The calculation results are presented in Table (1), demonstrating a monotonic increase in capacity loss with rising pulse amplitude, with the most severe degradation (44.37%) observed at 400 mA pulse. Figure (4) and Figure (5) confirm this trend visually.

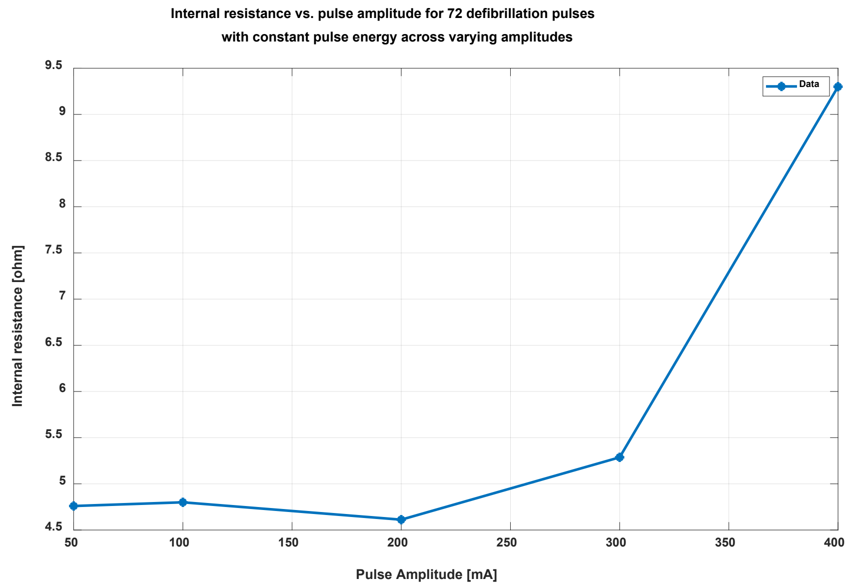

Figure (5)

Figure (4) illustrates the experimentally observed trend of internal resistance growth as a function of pulse amplitude for primary CR3677 LiMnO2 cells subjected to 72 high-rate defibrillation pulses, each delivering 30 Joules of energy. The internal resistance values were derived by averaging voltage drop-to-current ratios measured during eight DCIR (Direct Current Internal Resistance) test sequence following pulse-induced accelerated aging. The plot reveals a clear nonlinear increase in internal resistance with pulse amplitude: minimal change is observed at low C-rates (50 mA – 200 mA), with resistance changes ranging between 0% and –2%. However, at 300 mA, a noticeable increase of ~12% is observed, and at 400 mA, the resistance surges by nearly 95%. The results suggest that pulse amplitude is a dominant stressor in resistance-driven aging, reinforcing the importance of incorporating C-rate or pulse amplitude specific aging protocols in AIMD battery assessment.

Python and MATLAB code for implementing the pulse-induced accelerated aging experiment for identifying capacity loss and internal resistance growth in primary lithium cells are provided with this RST.

The following four Python scripts are for reading, extracting and concatenating the required data from exported Excel data files generated by ARBIN Data Watcher:

- Excel2text_CR3677_50mA_200s.py
- Excel2text_CR3677_100mA_100s.py
- Excel2text_CR3677_200mA_50s.py
- Excel2text_CR3677_300mA_33s.py
- Excel2text_CR3677_400mA_25s.py

The following two MATLAB files are used to read and analyze pulse-induced accelerated aging experiment data. The data is first processed using Python and saved as a text file, then imported into MATLAB and saved as a .mat file for further analysis.

- Cell_1-5_CR3677_37C_50_100_200_300_400mA.mat
- CR3677_Pulse_Aging.m

APPENDIX D

ARBIN Data Analysis and Visualization for Pulse-induced accelerated aging experiment

Plot the capacity loss and internal resistance growth obtained in step 5 against the applied C-rate or pulse amplitude for all test groups. The plots demonstrate the aging trend of the cells as a function of pulse amplitude. They also quantify the pulse-induced capacity loss after 72 defibrillations at each specified amplitude.

In this step we explain how we read the recorded data from ARBIN LBT20084 and ARBIN BT2000. The data is accessible through ARBIN “Data watcher.exe” software. The Data Watcher software by ARBIN displays the recorded data for each experiment individually. Since we conducted multiple experiments to investigate the aging trend as a function of a control input, namely the pulse amplitude, we exported this data from ARBIN and analyzed it using external tools such as MATLAB. Each experiment generated a large volume of data due to the long test duration and high sampling frequency. Therefore, the data of a single experiment was split into multiple Excel files by ARBIN LBT20084, and in multiple Excel sheets in a single Excel file by ARBIN BT2000. To analyze trends across tests (e.g., how aging varies with pulse amplitude), the data was consolidated into a single, easy-to-import file. We developed the two attached Python scripts to automate this process. One script consolidates the relevant data from multiple Excel files into a single text file for the ARBIN LBT 20084 system, and the other does the same for ARBIN BT 2000, where data is stored across multiple Excel sheets instead of files.

To run the Python code, first export the data for each experiment from the ARBIN Data Watcher software. Make sure to name the exported Excel files properly and save them in a dedicated directory. For example, in the Python script described below, the input file is named: “CR3677_37C_50mA_200S_72P_Cap_Channel_1_Wb_1.xlsx”

This filename indicates that:

1- The experiment was conducted on a CR3677 lithium battery cell.
2- The cell was tested in a 37°C thermal chamber.
3- The test was conducted on Channel 1 of the ARBIN LBT20084 system.
4- The cell was part of subgroup 1, which was subjected to a 50-mA constant-current pulse for 200 seconds.
5- The test scenario involved 72 pulses, hence the label “72P”.

The provided Python script is designed to read and consolidate such Excel files. It extracts only the relevant columns of interest (e.g., time, voltage, current, capacity) and writes the combined data into a single text file that is formatted for further analysis in MATLAB.

Python Script Description: Reading and Combining Data from ARBIN LBT20084 Exports:

1- <u>Set Output File Name:</u>
All extracted data is written into a text file named:
“Cell_1_CR3677_37C_50mA_200s_combined.txt”

2- Define Columns to Extract:
The script specifies and pulls only four columns of interest from each Excel file:
'Test Time (s)', 'Current (A)', 'Voltage (V)', 'Discharge Capacity (Ah)'

3- Locate Excel Files:
It assumes all Excel files are in the same folder as the script (directory = ".").
The Excel files are named in a numerical sequence:
(e.g., CR3677_37C_50mA_200S_72P_Cap_Channel_1_Wb_1.xlsx, ..._2.xlsx, etc.).

It loops through these file indices until it encounters a missing file, at which point it exits the loop.

4- Read and Extract Data:
For each file, it attempts to read the sheet Channel-1_1 and extract only the specified columns.
If the file can't be read (e.g., due to missing sheet or corruption), it skips to the next.

5- Write Data to Output: Each row from each file is written to the output .txt file.

6- Save the result: After processing all Excel files for the experiment, the merged output is saved as: "Cell_1_CR3677_37C_50mA_200s_combined.txt" in the current working directory.

Python Script Description: Reading and Combining Data from ARBIN BT2000 Exports:

1- Sets output file name:
Creates CR3677_37C_400mA_25S_72p.txt as the final combined output file.
This output file stores data for the CR3677 cell at 37°C under 400 mA pulses for 25 seconds (subgroup 5).

2- Prepares to collect data from each sheet across all files.
Filters sheet names:
Identifies sheets with names like Channel_1-012_001, Channel_1-012_002, etc. using a regular expression (Channel_1-012_\d+).
These are the sheets where the actual test data is stored in ARBIN BT2000 exports.

3- Defines columns to extract:
The script specifies and pulls only four columns of interest from each Excel file:
'Test Time (s)', 'Current (A)', 'Voltage (V)', 'Discharge Capacity (Ah)'

4- Loops through each Excel sheet:
Identifies matching sheet names. Reads each matching sheet and extracts the four desired columns.

5- Appends each dataset to a unified list (all_data).

6- Concatenate all data into one data frame:
   Merges the selected data from all sheets into one large data frame (final_data).

7- Exports to a text file:
   Saves the final combined data to CR3677_37C_400mA_25S_72p.txt.

Important notes on Python files for users:

Since we are conducting multiple tests (subgroup 1 to 5 for 15 cells across different pulse amplitudes), we need to run the script multiple times, updating the file names each time. Alternatively, if all exported Excel files are saved in a single directory, you may modify the script logic to automatically loop through all relevant test files and combine their data in one or more output files.

MATLAB analysis of accelerated aging data exported from ARBIN and converted to text file

After converting the ARBIN data from Excel to .txt format using the provided Python scripts, and importing these text files into MATLAB for further processing, the following steps are performed for analyzing capacity loss and internal resistance growth for each tested cell:

1- Import Data and Save as .mat Files:
   Load each .txt file into MATLAB, combine all 5 cells data of each group and save it as a .mat file for easy and fast access in the analysis workflow. For example, the attached .mat data file is from the first 5 cells of the experiment:
   (Cell_1-5_CR3677_37C_50_100_200_300_400mA.mat)

2- Identify the Constant Current–Constant Voltage (CCCV) Phase:

   To locate the CCCV phase in the post-aging test results, examine the discharge profile where the cell is discharged at a constant current (C/50) until it reaches the cut-off voltage (typically 2 V), followed by a constant voltage hold at 2 V. The CCCV phase begins at the start of this discharge and ends when the current falls below the defined cut-off threshold (e.g., 4 mA). This segment reflects the total usable capacity and is used for quantifying post-aging capacity retention.

3- Determine Capacity up to Cut-off Current

   Define the cut-off current threshold as 4 mA. This represents the termination point of usable capacity. For each CCCV phase:

   a. Locate the time at which the discharge current drops to 4 mA.

   b. Integrate the capacity delivered up to this point (or read the measured capacity at this time stamp of 4mA cut-off current if recorded) to quantify the usable post-aging capacity.

4- Calculate Total Capacity Used

   Add the capacity used during the 72-pulse aging test to the capacity measured in the CCCV discharge (up to 4 mA cut-off) to obtain the total available capacity after aging.

5- Compare with Fresh Capacity

Compare each aged cell's total available capacity with the baseline fresh cell capacity (measured in Step 2 of the protocol).

a. Capacity Loss = Fresh Capacity – Aged Total Capacity

b. Express the loss as a percentage of the fresh capacity.

6- Measure internal resistance growth

Use the average voltage drop across the four dual-pulse DCIR events to compute the internal resistance.

Average the eight resistance values (two per dual-pulse set) for each cell to estimate the resistance growth post-aging.

Compare each aged cell's internal resistance with the baseline fresh cell internal resistance (measured in Step 2 of the protocol).

Express the internal resistance growth as a percentage of the fresh cell's value.

7- Repeat for all cells in each group and subgroup

Perform the above steps for all cells in the test to account for variability and ensure statistically reliable results.

8- Plot Aging Trends vs Pulse Amplitude

a. Plot capacity losses and internal resistance growths as a function of pulse current amplitude (e.g., 50, 100, 200, 300, 400 mA) to identify how pulse magnitude influences degradation.

The capacity loss and internal resistance growth observations and analyses are presented and explained in detail in the following manuscript:

Pulse-induced Capacity Degradation Identification with an Accelerated Aging Test Protocol for Non-rechargeable Lithium Batteries in Active Implantable Medical Devices | BIOMED | ASME Digital Collection

Appendix C presents the MATLAB-plotted results and accompanying analysis used to identify pulse-induced accelerated degradation, specifically capacity loss and internal resistance growth, based on the data from Group 1 cells following the complete test procedure described above.

FDA software disclaimer

This software and documentation (the " Accelerated_Aging_TECM_Model_LiMnO2_Pulse_001.m", "DOD_OCV_Curve_LiMnO2.mat", "Capacity_Loss_vs_C_Rate_Pulse_Aging_CR3677.m", "Cell_1-5_CR3677_37C_50_100_200_300_400mA.mat", "CR3677_Pulse_Aging.m", "Fresh_CR2477_Cell_1_and_2_37C_cccv_C50.m", "Fresh_CR2477_Cell_1_and_2_37C_cccv_C50.mat", "Three_groups_Cap_loss_IR_varing_Pulse_Amp.m", "excel2text_CR3677_50mA_200s.py", "excel2text_CR3677_Pulse_300mA_33s.py" "CR3677_37C_45C_50C_W_2_4_6.m", "CR3677_37C_45C_50C_W_2_4_6.mat", "CR3677_Arrhenius_Analysis_Week_2_4_6.m") were developed at the Food and Drug Administration (FDA) by employees of the Federal Government in the course of their official duties. Pursuant to Title 17, Section 105 of the United States Code, this work is not subject to copyright protection and is in the public domain. Permission is hereby granted, free of charge, to any person obtaining a copy of the Software, to deal in the Software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, or sell copies of the Software or derivatives, and to permit persons to whom the Software is furnished to do so. FDA assumes no responsibility whatsoever for use by other parties of the Software, its source code, documentation or compiled executables, and makes no guarantees, expressed or implied, about its quality, reliability, or any other characteristic. Further, use of this code in no way implies endorsement by the FDA or confers any advantage in regulatory decisions. Although this software can be redistributed and/or modified freely, we ask that any derivative works bear some notice that they are derived from it, and any modified versions bear some notice that they have been modified.