1 An Algorithm to Estimate Lithium-Ion Battery Lifetime

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2 Research Question / Research Goals

What problem is trying to solve ?

- Battery is a key component in many applications: Phone, Computer, Electric Vehicle => **Lifetime Projection?**
- Increasing demand of these systems/devices (Explosion incidents)=> **Safety and Efficiency Concerns**
- Long operational lifetime cannot be accurately determined => **Lifetime Projection?**
- How can the lithium-ion battery lifetime be estimated to provide information that ensures **safety, efficiency, and longevity of the battery?**

Research Goal

- **Develop a mathematical algorithm for modeling and predicting the battery lifetime for health monitoring**
- Analysis of a life time projections and expected SoC as a function of operating parameters and properties.
- **Formulate an architecture for model-based prognostics that will be applied for BHM (Battery Health Monitoring).**

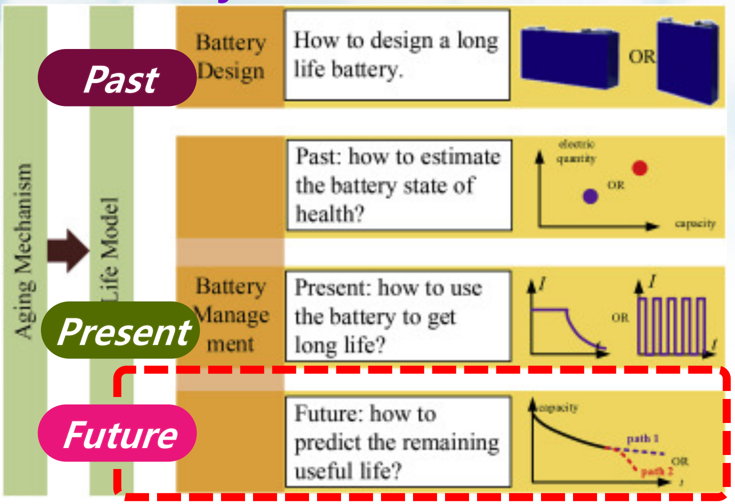


Fig. 1. Battery design and management issues based on the aging mechanisms and life model [Ref: 23].

3 Statement of Hypothesis / Approach /Method

Hypothesis

- When an electrochemical reaction happens, every electrochemical system, such as batteries, undergoes an **irreversible reaction** which gradually **decrease the performance** of the system.
- Thus, during this time, there will be an **indication of performance failure**.

Current Approaches / Existing Methods

Algorithm Based Approach

- Neural Networks [Ref: 1-3]
- Kalman Filter [Ref:4-7]
- Support Vector Machine [Ref:4,5,8,9]
- Bayesian [Ref: 4, 10, 11]
- Gaussian Process Regression [Ref:4,12]

Direct Measurements

- Coulomb/Ah Counting [Ref: 4,5, 7,13]
- Temperature Monitoring
- Gas Sensor
- EIS
- Capacity Testing/Cycle Counting
- OCV
- Voltage/Current/Power

[Ref: 14 – 19]

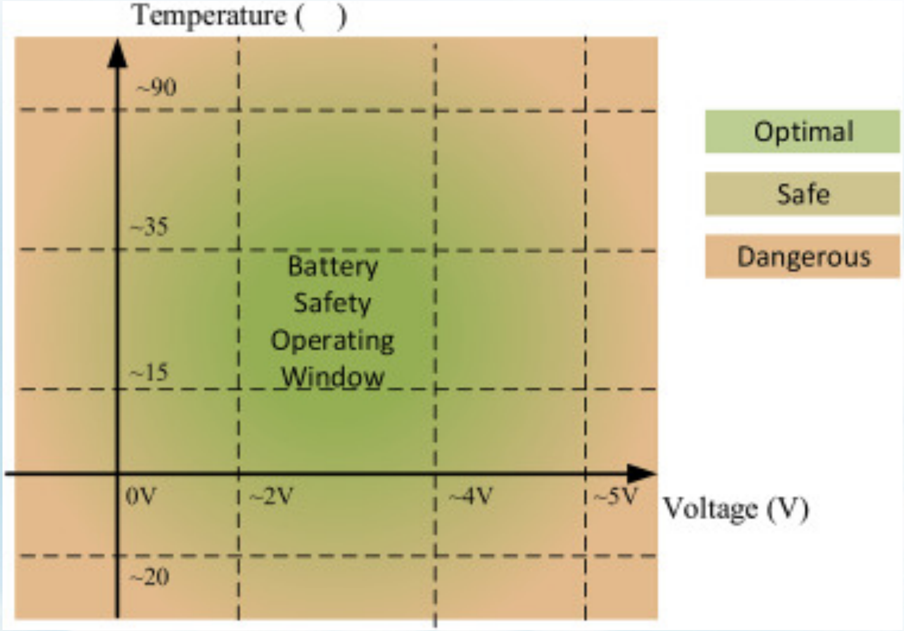
Other Techniques

- Destructive Methods [Ref: 4, 20]
- Piezoelectric/Pyroelectric Material [Ref: 21]

4 Battery Monitoring Parameter

Battery Monitored Parameters

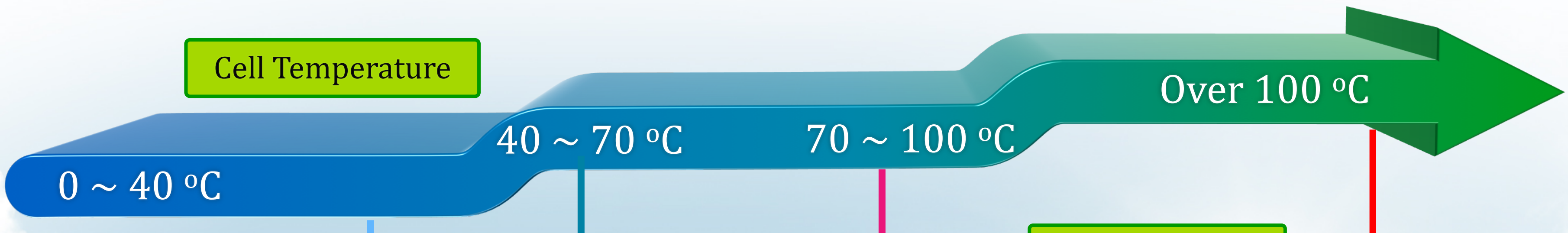
1	Voltage (v)	
2	Current (I)	
3	Power (P)	= 1 (Voltage) * 2 (I)
4	Resistance (R)	= 1 (Voltage) / 2 (I)
5	Temperature (°C)	
6	mAh	= 1 (mAh) * Time (charging/discharging)
7	Wh	= 1 (Voltage) * 6 (mAh)/1000
8	Gas Sensor Current	



Battery operating window [Ref:24].

4 Cell Failure Mode: Why Temperature ?

Battery Cell Failure Mode (Based on Cell Temperature)



- Li plating on electrode
- Anode dissolution

- Short circuit at high temp.
- SEI layer breakdown

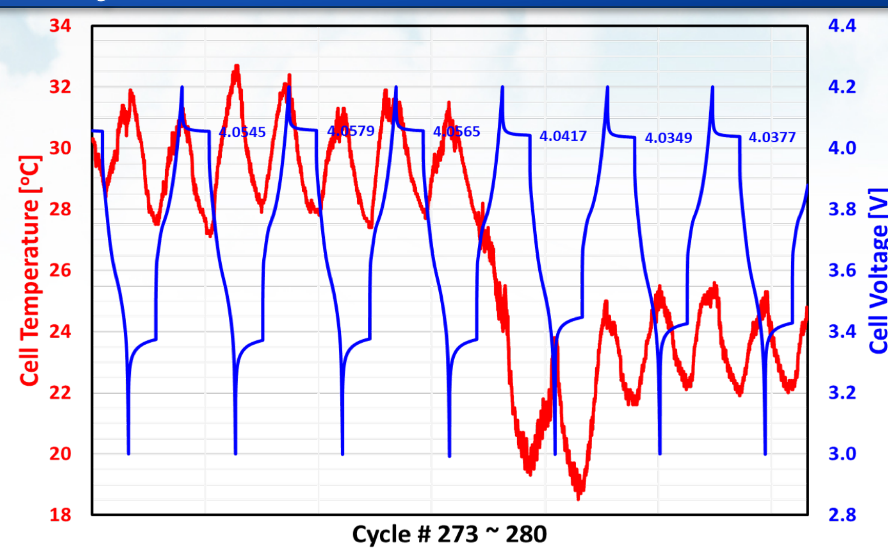
- Electrolyte Breakdown
- Internal Pressure buildup

- Cathode decomposition
- Cell oxidation (shells, castings etc.)

Response to Battery Failure

- Resistance Rise
- Internal Temperature Rise
- Capacity Drop
- Power Drop

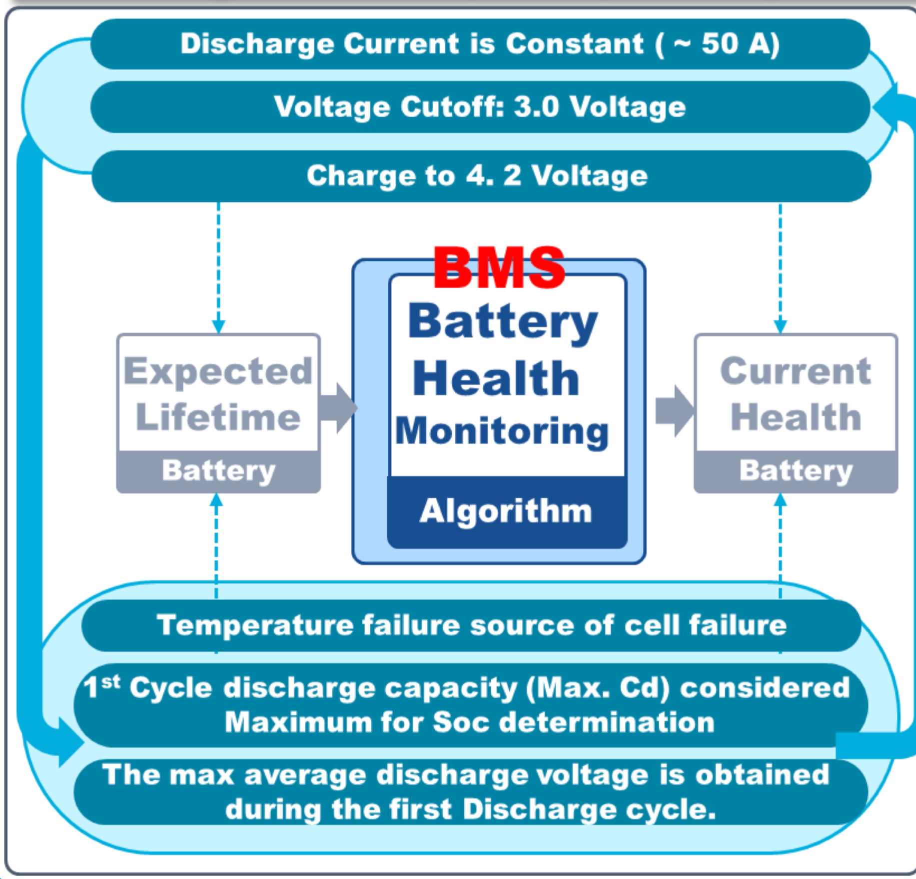
Battery Health Monitoring System !



5 Methods and Procedures for Battery Health Monitoring

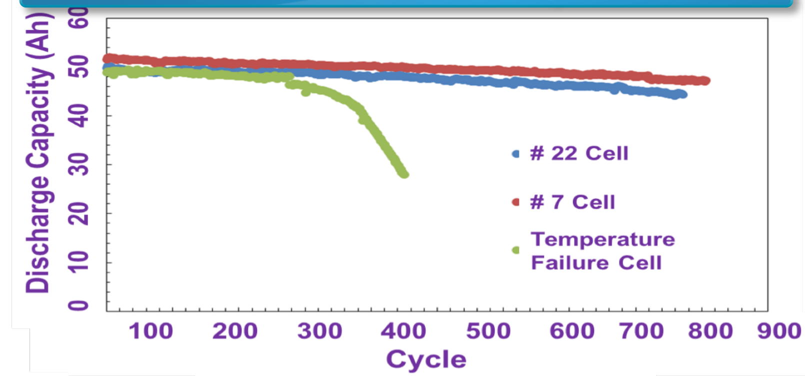
Input / Output / Control Parameter

Testing Procedure/Data /Assumption



- **Data Collected:** Voltage (V, Volts), Current (I), Time (s), Cycle number (n, cycles), Cycle at temperature limit error (z, cycle #).

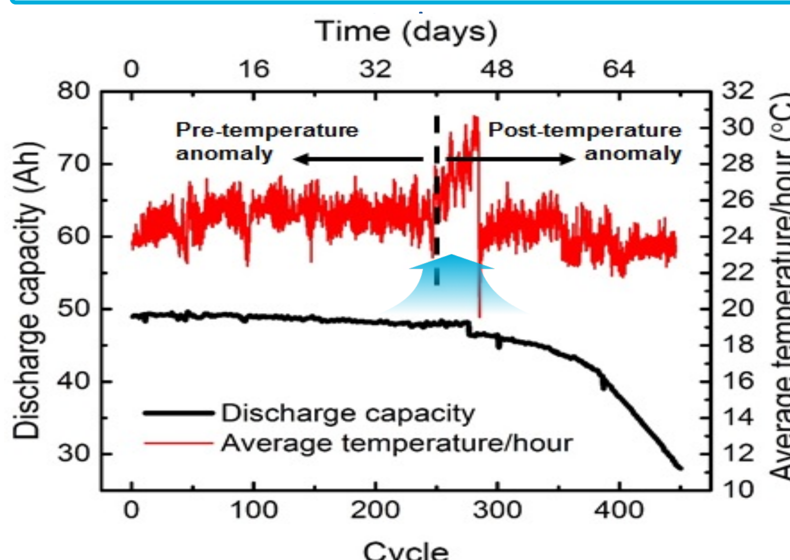
Lithium-ion Battery Test



Temperature Anomaly Region

(a) Pre-temperature anomaly – 1st to 250th Cycle

(b) Post-temperature anomaly – 251st to 450th

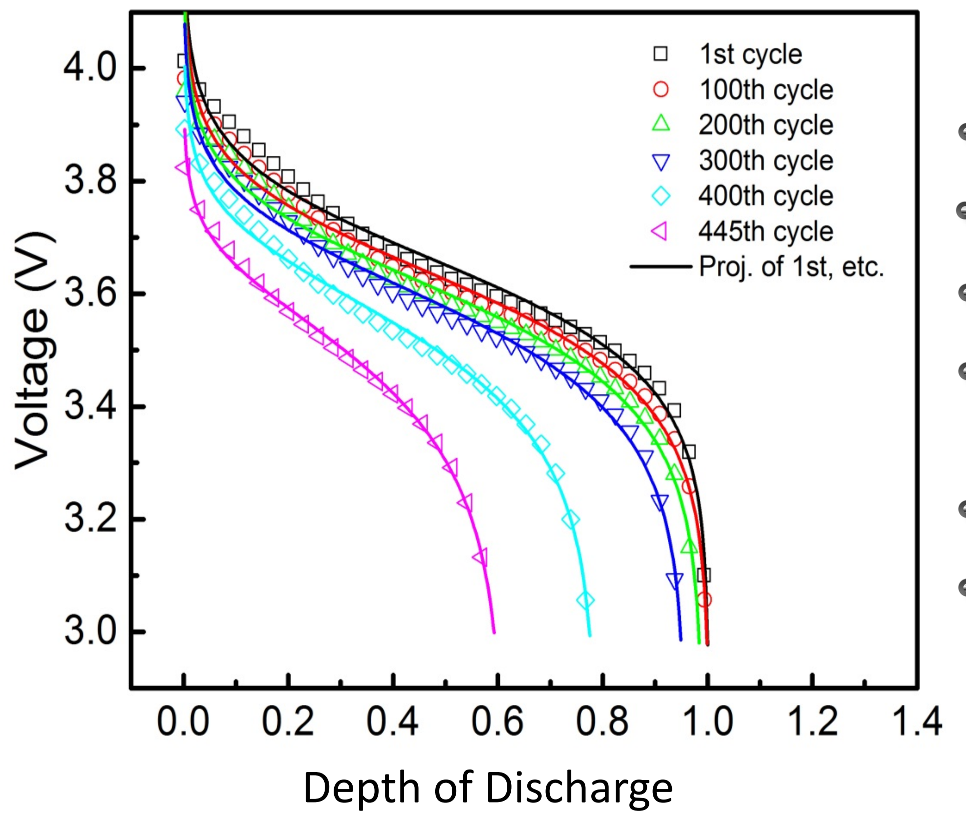


6 Results of Project

Voltage Profile Projections of the Lithium Test Cell as a Function of Cycle #, Single Temp., Limit Failure, and Projected SoC

$$V_{profile} = A(n,z)\left[1 - \log\left(\frac{n^{i(n,z)}}{(SOC_{max}(n,z) - n)^{j(n,z)}}\right)\right]$$

$$\{A(n,z), i(n,z), j(n,z), SOC_{max}(n,z)\} = A_0 e^{r(n-z)} + an + b$$



Sub-functions of Equation

- $A(n,z)$ – *projected avg. discharge voltage*
- $SOC_{max}(n,z)$- projected C_d/max. C_d
- $i(n,z)$ – 1st turn curvature factor
- $j(n,z)$ – 2nd turn curvature factor

- *Symbol = Measurments*
- *Line – Prediction*

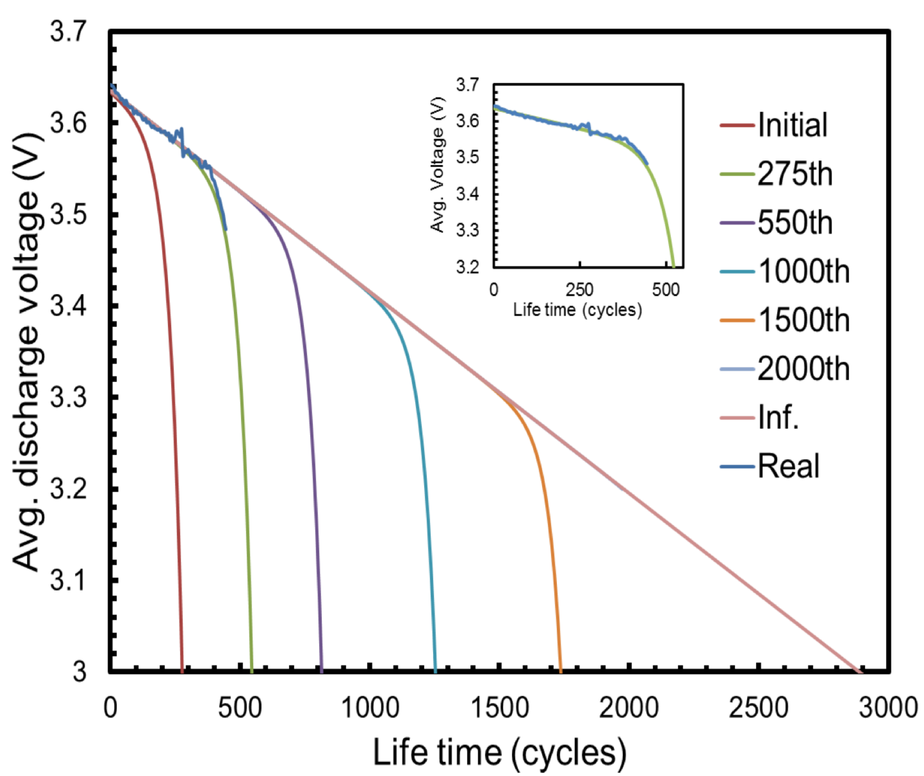
Results of Project

Life time projections of average discharge voltage of the lithium test cell as a function of cycle # and a single temp. limit failure, with cut-off voltage of 3.0 V

$$V_{avg}(n, z) = A_0 e^{r(n-z)} + ax + b$$

Initially, z=+∞ (or a large number ≫ maximum lifetime, 100,000 etc.).

When a temperature anomaly occurs, set z=n_($temp.\ anom.$)



Variable of Equations

- ***V_avg (n,z)* - avg. discharge voltage, V**
- ***n* – cycles ran**
- z – $cycle\ \#\ @\ temp.\ limit\ failure$
- A_0, r, a, b – $constants\ of\ equation$

Constants of Equations

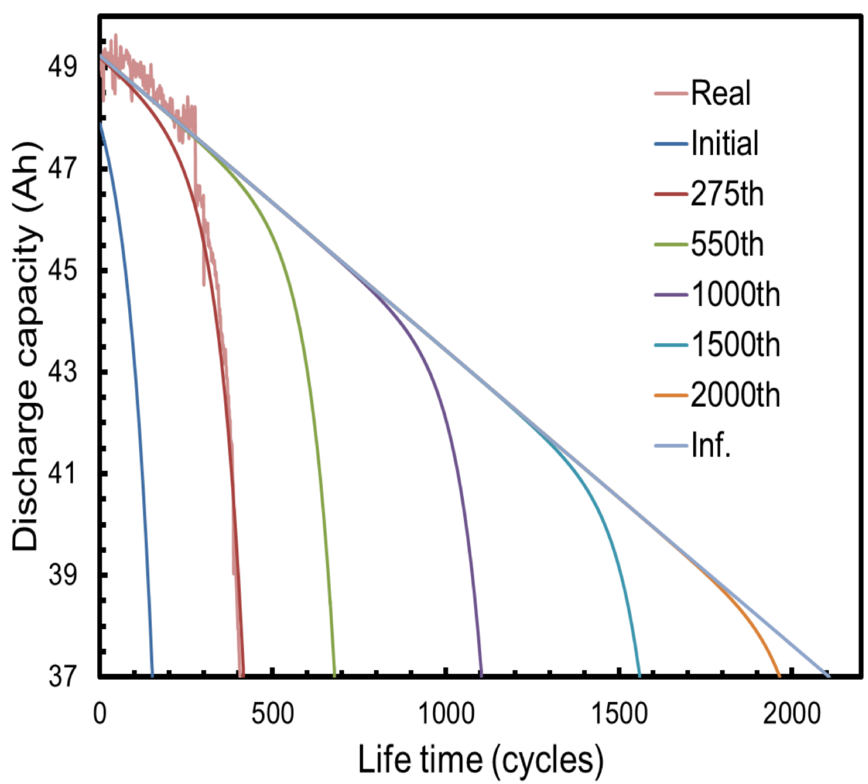
- $A_0 = -1.8\times10^{-3}$ V
- r=0.02091 cycle-1
- $a = -2.2\times10^{-4}\ V/cycle$
- $b = 3.6355\ V$

Results of Project

Life time projections of the lithium test cell as a function of cycle # and a single temp. limit failure. Cut-off is based on 75% of 1st cycle discharge capacity, ~ 37 Ah

$$C_d(n,z) = A_0 e^{r(n-z)} + an + b$$

Initially, $z = +\infty$ (or a large number $\gg$ maximum lifetime, 100,000 etc.).
When a temperature anomaly occurs, set $z = n_{temp.anom.}$



Variable of Equations

- $C_d(n,z)$ - discharge capacity, Ah
- n – cycles ran
- z – cycle # @ temp. limit failure
- A_0, r, a, b – constants of equation

Constants of Equations

- $A_0 = -1.35659$ Ah
- $r = 0.01405$ cycles-1
- $a = -5.8 \times 10^{-3}$ Ah/cycle
- $b = 49.23$ Ah

7 Discussion

Predictions of battery lifetime and state-of-health (SoH) based on a limit of 75% 1st cycle avg. discharge voltage (Vavg.) versus cycle (n) for various temperature failure occurrences (z).

Temp. failure (z)	Battery SoH (% $V_{avg.}$ remaining)					
	100%	95%	90%	85%	80%	75%, Full life
500	$n = 1$	645	725	755	775	785
1000	$n = 1$	825	1190	1240	1265	1280
1500	$n = 1$	825	1595	1715	1750	1770
$+\infty$	$n = 1$	825	1655	2475	3305	4130

- Note: $z = +\infty$ means that no temperature failure has occurred!
- $z = 500$ means that a temp. failure was recorded at the **500th cycle**.
- Example: If temp. failure occurs during the **1000th cycle**, the full lifetime of the battery is projected to be **~1280 cycles (75% SoH / Full Life)**.
- Example: A battery that records a temp. failure during the **1500th cycle** is projected to have a $SoH = 90\%$ at the **1595th cycle**.

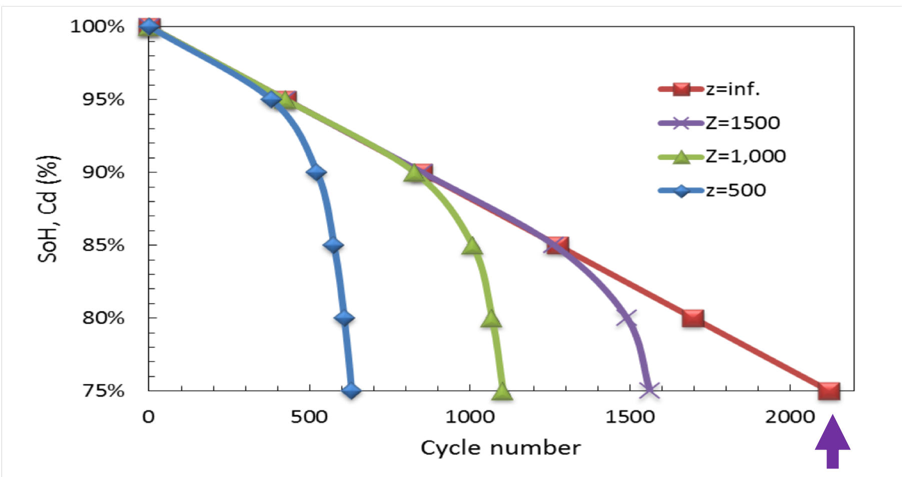
7 Discussion

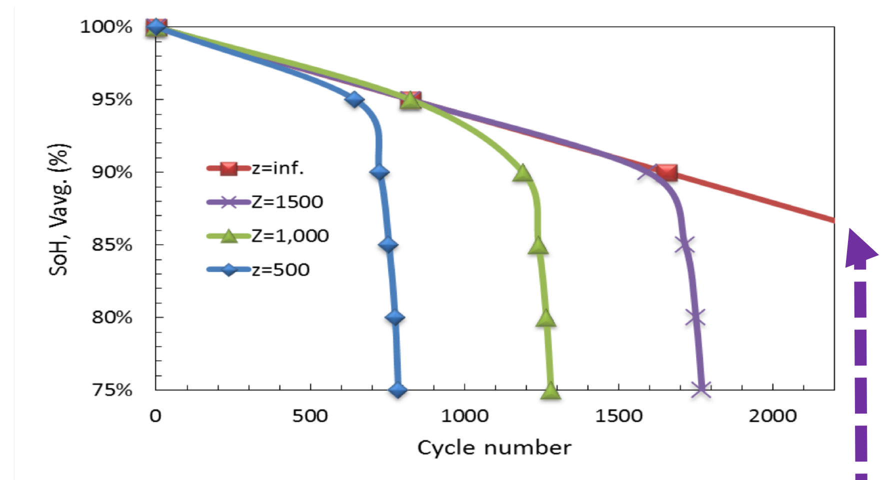
Predictions of battery lifetime and state-of-health (SoH) based on a limit of 75% 1st cycle discharge capacity (Cd) versus cycle (n) for various temperature failure occurrences (z).

Temp. failure (z)	Battery SoH (% C_d remaining)					
	100%	95%	90%	85%	80%	75%, Full life
500	$n = 1$	381	524	577	609	632
1000	$n = 1$	425	829	1009	1070	1104
1500	$n = 1$	425	853	1264	1491	1562
$+\infty$	$n = 1$	426	850	1274	1698	2122

- Note: $z = +\infty$ means that no temperature failure has occurred!
- $z = 500$ means that a temp. failure was recorded at the 500th cycle.
- Example: If temp. failure occurs during the **500th cycle**, the full lifetime of the battery is projected to be ~**632 cycles (75%: SOH / Full Life).**
- Example: A battery that does not record a temp. failure is projected to have a $SoH = 80\%$ at the ~**1698th cycle**.

Battery lifetime and State-of-Health (SoH) based on required discharge capacity and average discharge voltage for various temperature failure occurrences (z).

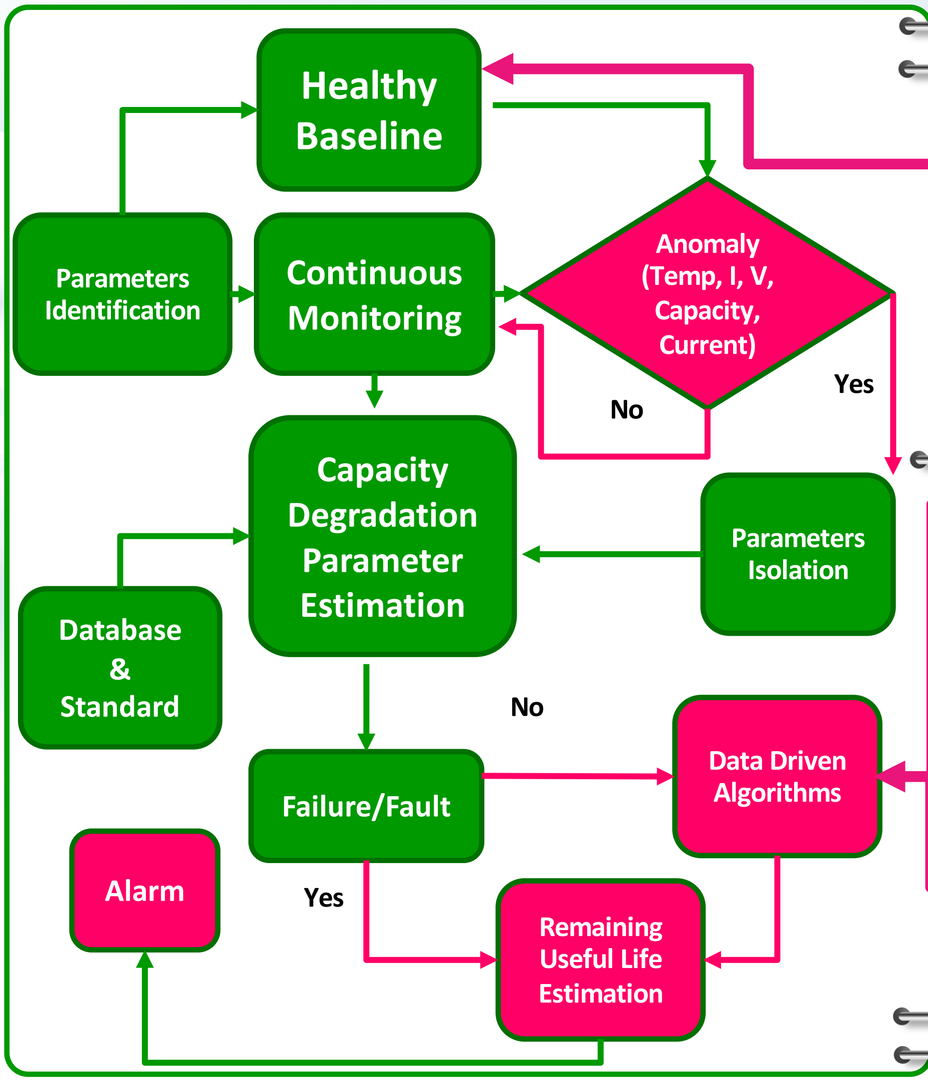




- Based on 75% 1st cycle discharge capacity/SoH/V_avg in this project, the **Max. projected lifetime** of a current lithium-ion battery is around **2100 ~ 4130 cycles**. (Ref: [22] 4.20V/cell typically delivers 300–500 cycles. 4.10V/cell, to 600–1,000 cycles; 4.0V/cell 1,200–**2,000** and 3.90V/cell should provide 2,400–**4,000** cycles.
- **Discharge capacity will limit the battery lifetime** before average discharge voltage
- While the Cd limit is reached first, the **average voltage the battery can deliver drops off significantly faster after a temperature failure**!
- **Problem not expecting:** which cell was bad/good, which was overcome by utilizing 25 batteries
- This is an **improvement over current methods** of battery lifetime estimation because it is **more efficient** unlike disruptive methods, **less complex** (amount of training data/cost/time-consumption) than other algorithm-based methods, and can be **applied to a broad-range of applications** unlike direct methods.

8 Conclusion

The developed algorithm to estimate the lifetime of Lithium-ion Battery



SoC correction

SoH Estimation Algorithm

$$V_{profile} = A(n,z)\left[1 - \log\left(\frac{n^{i(n,z)}}{(SOC_{max}(n,z) - n)^{j(n,z)}}\right)\right]$$

$$\{A(n,z), i(n,z), j(n,z), SOC_{max}(n,z)\} = A_0 e^{r(n-z)} + an + b$$

$$C_d(n,z) = A_0 e^{r(n-z)} + an + b$$

Initially, $z = +\infty$ (or a large number $\gg$ maximum lifetime, 100,000 etc.). When a temperature anomaly occurs, set $z = n_{temp.anom.}$

8 Conclusion

- This project proposed **three separate mathematical equations and one algorithm to predict a lifetime of battery as expected**.
- Prediction of lifetime based on required discharge capacity and avg. discharge voltage (75% of 1st cycle V_avg. and Cd) proposed as follows:
    - $V_{profile} = A(n,z)\left[1 - \log\left(\frac{n^{i(n,z)}}{(SOC_{max}(n,z)-n)^{j(n,z)}}\right)\right]$
    - $V\_avg\ (n,z) = A\_0\ e\hat{}r(n-z) + ax + b$,
        - This equation predicts the lifetime of the battery based on the required average voltage during discharge as a function of the occurrence of a temperature limit failure. V_avg. required is equal to 75% of the initial avg. discharge voltage.
    - $C\_d\ (n,z) = A\_0\ e\hat{}r(n-z) + an + b$,
        - This equation predicts the cell lifetime based on the specific discharge capacity, considering 75 % of the maximum specific capacity as minimum admissible.
- This project applies to **electric vehicles, computers, mobile phones, and energy storage systems**.
- Tips for extending the lifetime of lithium-ion batteries can be suggested: Minimize exposure to high/low temperature, minimize time spend at 100% charge/10% charge, and avoid high moisture environments.

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10 Summary

Q1: Engineering Problem & Objectives

- Batteries are crucial in many applications
- Reports of explosion events due to batteries
- Increasing demand of these systems/devices
- Develop a mathematical algorithm for modeling and predicting the battery lifetime for health monitoring of battery.
- Analysis of a life time projections and expected SoC as a function of operating parameters and properties.
- Formulate an architecture for model-based prognostics that will be applied for BHM (Battery Health Monitoring).

Q3: Data Analysis & Results

- 3 Governing Equations were derived from this project. Lifetime prediction as a function of cycle number and temperature failure:
- $C_d(n,z) = A_0 e^{r(n-z)} + an + b$
- The equation for the voltage profile versus SoC follows a logarithmic equation as follows:
- $V_{profile} = A(n,z)\left[1 - \log\left(\frac{n^{i(n,z)}}{(SOC_{max}(n,z)-n)^{j(n,z)}}\right)\right]$

$\{A(n,z), i(n,z), j(n,z), SOC_{max}(n,z)\} = A_0 e^{r(n-z)} + an + b$

Q2: Project Design

- Temperature, V, I, P, Cd data were recorded throughout the functioning of the cell during charging, discharging, and subsequent resting steps.
- The failure of the battery has been modeled to derive equations for predicting the capacity as well as the lifetime as a function of the cycle number, a cut-off discharge capacity (75 % of initial discharge capacity), and temperature.
- The failure of the battery has been modeled to consider the failure as a function of the cycle number and a single temperature limit failure.

Q4: Interpretation & Conclusions

- The flowchart for the mathematical analysis of the cell cycling and developed algorithm provides continuous estimation of remaining lifetime.
- Discharge capacity will limit the battery lifetime before Vavg.
- Based on 75% 1st cycle discharge capacity, the max. projected lifetime of the battery is ~2100 cycles.
- While the Cd limit is reached first, the avg. voltage the battery can deliver drops off significantly faster after a temperature failure.