

Thermal Runaway Analysis and Prevention Strategies for Lithium-Ion Batteries

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Abstract: Lithium-ion batteries have been used in batteries of electric vehicles, consumer electronics, and industrial test devices in a large degree because of their large energy density and their charging ability for many times. Cyclic and repetitive testing Environmental conditions the Charge Discharge Charge (CDC) testing environments expose the batteries to repeated cycling, large current loads, intense and many state-of-charge transitions, and very high thermal and electrochemical stress levels. Such conditions enhance a threat of thermal runaway that is a severe safety issue that involves the uncontrolled heat generation resulting in a fire or an explosion. In this paper, the phenomenon of thermal runaway in the work of lithium-ion batteries in CDC condition has been developed in detail. The experimental assessment was then repeated at various C-rates and ambient temperatures using real-time interactive thermal imaging, embedded thermocouples, and philosophical voltagecurrent in determining the initial signs of C - indication of thermal inconsistency. The paper also suggests a whole set of passive temperature control and active change on the battery management system (BMS), such as the dynamical feedback control on the temperature, active current control and the outlier forecasting etc. The findings indicate that the traditional BMS protection plans cannot be used in long-term situations of CDC testing. The suggested multilayer prevention approach is an efficient tool that will eliminate the threat of thermal runaway and enhance operational safety and test reliability. The results set a practical idea on how to test batteries more safely, and their practical advice can be used in longer-term solutions to a larger-scale approach to improving thermal performance in real-world lithium-ion based battery systems.

Keywords: Lithium-ion batteries; Thermal runaway; Charge–discharge cycling; Battery management system; Thermal monitoring; Energy storage safety

I. INTRODUCTION

Li-ion batteries (LIBs) are now the standard energy storage technology in electric cars, consumer electronics, grid-level storage, and industrial test and measurement because of their high energy density, long cycle life and desirable efficiency properties [1], [6]. In spite of these benefits, safety is a significant issue of concern, especially when the operating conditions are extreme. Thermal runaway is the most dangerous type of failure mode, which may result in fire, explosion, and domino-like failures in other cells or battery packs [1], [5].

Thermal runaway is a complicated multi-phase process that occurs due to the internal or external abuse environment including overcharging, high current operation, high temperature, or mechanical damage [2], [11]. Upon activation, a series of exothermic reactions such as solid -electrolyte interphase (SEI) decomposition, electrolyte breakdown and degradation of the cathode material lead to the rapid heat production which is beyond the heat dissipation capacity of the cell [1], [5]. Recent experiments have quantitatively described the onset temperature and heat release rate and propagation behavior of thermal runaway in lithium-ion cells [2], [5].

Repeated charge-discharge cycling is an effective way to enhance degradation processes which make thermal instability. C-rate operation causes lithium plating, growth of internal resistance and electrolyte decomposition all of which increases heat production in the following cycles [16], [17]. Moreover, cell chemistry is a crucial factor in thermal behavior; cell chemistries of lithium iron phosphate (LFP) have superior thermal performance than nickel manganese cobalt (NMC) chemistries, despite having a lower energy density [7]. The results show that chemistry selection is important in safety-critical testing scenarios.

Charge-Discharge-Charge (CDC) machines are widely applied in research laboratories and manufacturing companies for the measurement of the performance, aging and reliability of battery under controlled but aggressive cycling conditions. Definitely in contrast to real world operations, CDC testing requires cells that are operated under continuous cycling, repeated state-of-charge and constant high current over an extended period of operation. It is known that these conditions can cause cumulative thermal and electrochemical stresses to be significantly high and CDC environments have been rather prone to thermal runaway events [1], [16].

The use of traditional safety system and Battery Management Systems (BMS) is anchored on a primary concept of threshold dependent safeguards which includes, but is not restricted to, voltage cut offs, current and surface temperature. These methodologies can be of great benefit but they will fail badly at any early thermal anomaly detection in long cycling test protocols provided that their nominal operating conditions are met [4]. The latest research has mentioned the significance of advanced early-warning schemes (such as state-of-safety indicators and data-driven prediction schemes) in detecting the incipient runaway behaviour in advance of the progression by a failure that is catastrophic in nature [3], [14], [15].

This paper will be addressing these issues through the study of the behavior of thermal runaway in the case of lithium-ion batteries undergoing the CDC testing conditions. Experimental analysis environmental solutions with systematic level strategies to mitigate against them are incorporated with the system-level strategies like passive thermal insulation [8], improved material selection [9], and active BMS enhancement relying on the real time thermal analysis and prediction of diagnostics [3], [14]. The proposed solution will be in a position to assist in improving the safety, consistency and repeatability of the battery testing conditions as well as providing a scalable information, which can be used within a more realistic system of power storage.

II. EXPERIMENTAL SETUP AND CDC METHODOLOGY

The experimental setup and methods is to study the thermal, electrical and electrochemical properties of lithium ion cells when they are subjected to controlled Charge Discharge Charge (CDC) cycles. The main objective is to determine the early signs of instability, validate the ways of cell failure and then use the preventive measures and ensure the operation safety.

A. CDC System Overview

The CDC system is a multi-channel charge -discharge machine, which can deal with 64 cells at once. The voltage, current and temperature in all channels are independently monitored and provides the channel with easy control and safety. The system also integrates:

- High-resolution temperature sensors and infrared imaging for thermal surveillance.
- Voltage and current monitoring circuits for real-time performance evaluation.
- A predictive Battery Management System (BMS) for anomaly detection and automated shutdown.
- Safety measures such as temperature shutoff, deviation of voltage and physical barriers.

Fig.1 is a description of the concept layout of the CDC System including cell arrays, sensors, data acquisition and safety modules.

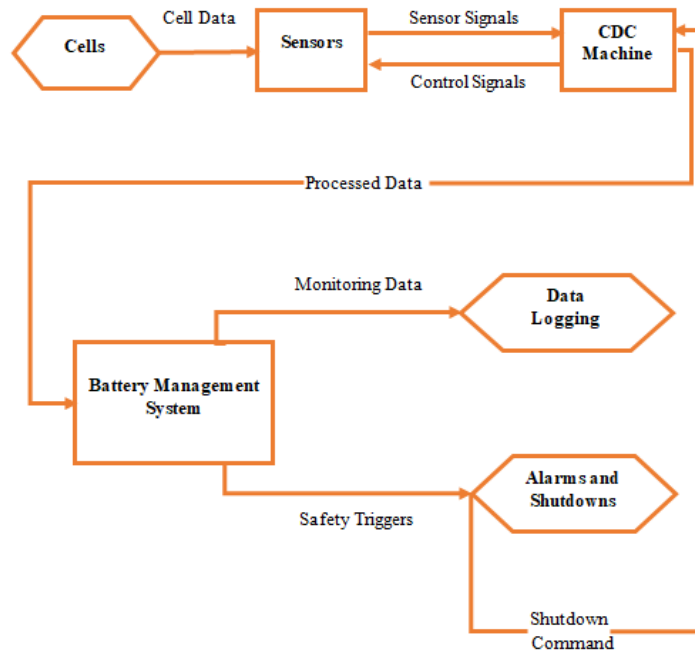


Fig. 1: Block Diagram of CDC Experimental Setup

B. Experimental Methodology

The CDC technique involves 3 major stages which includes cell selection, controlled cycling and real time monitoring.

1) Cell Selection and Pre-Screening

Before CDC test, all the cells are subjected to:

- Visual inspection for deformation, leakage, or swelling.
- Capacity verification under standard conditions.
- Only cells passing the pre-screening criteria proceed to the CDC testing phase.

2) Charge–Discharge–Charge Protocol

The following standardized protocol of cell cycle is given:

Operation	Condition	Purpose
Initial Charge	50% SOC → 100% SOC (3.2 V → 3.65 V), ~1.5 h	Stabilize the cell under controlled charging
Discharge	100% SOC → 0% SOC (3.65 V → 2.8 V), ~1 h	Monitor dynamic performance under load
Final Charge	0% SOC → 50% SOC, ~1.5 h	Return cell to storage-safe SOC

Every operation is controlled by constant-current / constant-voltage (CC-CV) control in order to ensure safe conditions of charging and discharging.

3) Real-Time Monitoring

The CDS system keeps watch on:

- Temperature:
 - Thermocouples for each channel.
 - IR imaging every 30 minutes.
 - Speed limit 1 (60 degrees Celsius) in order to detect the initial thermal aberrations.
- Voltage and Current:
 - Constant voltage drop, rising and deviation rate measurement.
 - Cutoff low-voltage 2.6V to prevent deep discharge.
- Error Handling:
 - Automatic shutdown of faults (critical errors).
 - Step termination detected open circuit.
 - Live notification of and creation of logs.

C. Data Collection and Analysis

The test data sets are as follows:

- Voltage curves.
- Current profiles.
- Temperature rise trends.
- Error logs, shutdown event logs, channel isolation logs.
- Hot spots identification by thermal images.

Analysis includes:

- Comparing stability between NMC and LFP chemistries.
- Detecting early-warning indicators of failure.
- Correlating physical symptoms with recorded logs.
- Validating the responsiveness of safety mechanisms.

D. Safety and Risk Mitigation

In a multi-layer approach to safety, testing integrity is guaranteed:

- Passive Controls:
 - Cells which are thermally stable (e.g., LFP).
 - Heat retardant insulation and required storage conditions.
- Active Controls:
 - Temperature cutoff (60°C).
 - Maximum intensity voltage threshold (max 2650 mV).
 - Automatic error and predictive BMS.
- Physical Protection:
 - Fireproof or electrolyte splash plexiglass barriers.
 - Sufficient ventilation and spacing.
 - Real time verification using thermal camera.

E. Validation of the Methodology

- Detection of abnormal thermal or electrical behaviour.
- Accurate identification of cell failures (internal short circuits, voltage collapse).
- Assessment of multi-layered safety measures.
- Comparative testing showing LFP cells exhibit higher intrinsic safety than NMC cells.
- Reproducibility across multiple test cycles and setups.

III. EXPERIMENTAL TEST AND IMPLEMENTATION

The experimental activity regarding the use of CDC experiments in the form of handling of cells, optimization of the device and a process line and continuous observation.

A. Battery Pack Preparation and Receiving Inspection

The inspection and storage process of any incoming cells and components are highly stringent to ensure the safety and performance:

- **Material Receipt and Verification:**
 - Visual inspection for defects such as swelling, leakage, or deformation.
 - Validation of specifications of the manufacturers.
- **Storage Conditions:**
 - Storage at low temperature (<28°C) and humidity control to inhibit degradation.



Fig. 2: Lithium-ion Battery Pack

B. CDC Machine Configuration

Cells are tested using a multi-channel Charge -Discharge-Charge (CDC) machine:

- **Machine Capabilities:**
 - Up to 64 cells can be tested at the same time.
 - Channel voltage, current and temperature independent channel monitoring.
- **Process Flow:**
 - Initial Charge: 50% → 100% SOC, ~1.5 hours
 - Discharge: 100% → 0% SOC, ~1 hour
 - Final Charge: 0% → 50% SOC, ~1.5 hours
- **Software Interface:**
 - Each channel displays real-time voltage, real-time current, real-time capacity and status.
 - The flags of abnormal behaviour and errors are automatically introduced into the light.



Fig. 3: CDC Machine Setup

C. Machine Settings and Safety Parameters

To avoid cell failures: machine configuration is important:

- **Voltage Control:** Maximum deviation limited to 2650 mV.
- **Error Processing:** Immediate halt of operations on open-circuit or abnormal voltage detection.
- **Predictive Safety:** BMS provides temperature, voltage, or current alarms which are activated automatically.

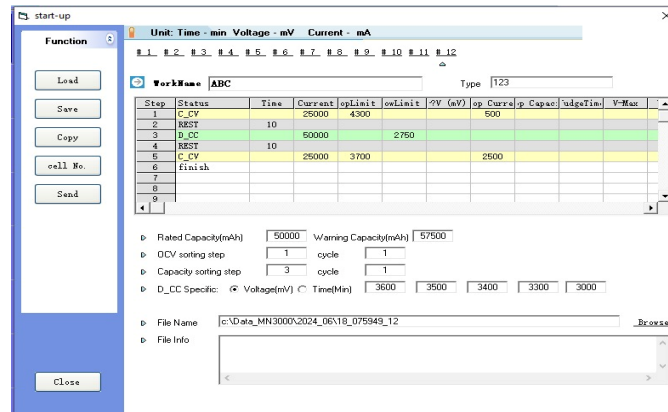


Fig. 4: CDC Machine Safety Parameter Configuration

D. Real-Time Monitoring and Data Logging

- Temperature Monitoring:
 - Thermal imaging on the IR every 30 minutes and thermocouples per channel.
 - Alarm threshold: 60°C.
- Voltage and Current Monitoring:
 - Voltage drop, rise rates and deviation continuously logged.
 - Cutoff low-voltage: 2.6 V to prevent deep discharge damage.
- Failure Detection:
 - Steep drop in voltages or reverse of current is registered.
 - The occurrence of failure is observed real-time and preventive action is taken.

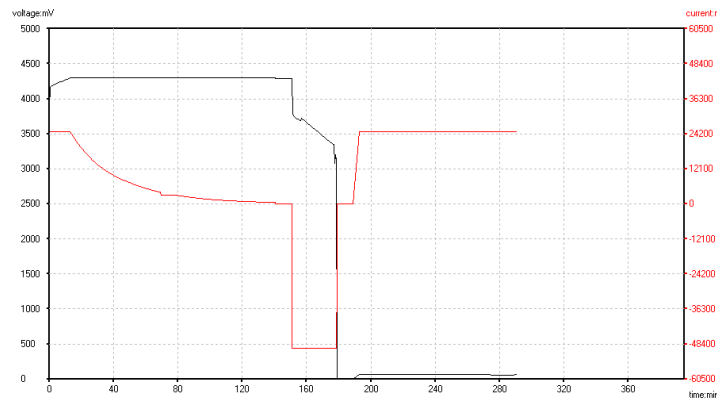


Fig. 5: Cell Failure Log

E. Module and Pack Assembly

- Cell Sorting and Grouping:
 - The cells were matched based on voltage (within 0.05V), internal resistance and capacity.
- Module Assembly:
 - Cells are also installed in modules with insulation papers to prevent short circuiting.
- Assembling Pack and Final Inspection:
 - Assembling was done with powder-coated metal enclosures and sealing strips.
 - Incident routing of charge/discharge and CAN communication cables.
 - Integrity checks done by air leak and functional tests.

F. Test Validation and Observations

- Voltage, current, and temperature curves recorded for NMC and LFP cells.

- NMC cells showed higher thermal risk; LFP cells exhibited superior safety.
- Real-time alerts prevented catastrophic failure and confirmed system reliability.

IV. RESULTS AND DISCUSSION

Charge-Discharge-Charge (CDC) tests provide the finer picture of the performance of the battery, failures, as well as thermal behavior. Other analysis also presents a comparison of Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP) cell, providing information about the safety precautions that can possibly be taken to avoid issues.

A. NMC Lithium-Ion Battery Test Results

A test of NMC cells, nominal voltage of 3.67 volts and rated capacity 58 Ah was been done through standard CDC test. Table 1. is a summary of the mechanical, thermal and electrical performance results.

Table 1: NMC Battery Test Report

Test	SOC	Key Conditions	Results (Voltage/Capacity Start → End; Max Temp)
Vibration (8h/3 axes, 2000Hz)	100%	RMS 27.8 m/s ²	4.34V/58.09Ah → 4.33V/58.08Ah
Mechanical Shock (6 directions)	100%	500 m/s ² , 6ms, 10/shock/axis	4.33V/58.08Ah → 4.32V/58.06Ah
Crush (hemisphere, 150mm dia.)	100%	Max 9124N, 5mm/s	OCV 4.34V (pre/post), 26.5°C
Temp. Cycling (30 cycles, -20°C to 65°C, BEV profile)	80%	w/ electrical operation	4.05V/47.11Ah → 3.04V/26.49Ah
External Short Circuit (<5mΩ, 10min)	100%	RT	4.33V → 4.56V, 93.2°C
Overcharge (1It to 2x max V)	100%	58A constant	4.35V, 42.1°C (tripped at 8.70V)
Forced Discharge (1It, 90min)	0%	58A	2.86V start, 53.5°C

Observations:

- NMC cells exhibited high energy density but moderate thermal stability.
- Thermal runaway risk is significant under overcharge or short-circuit conditions.
- No leakage or fire events were observed under standard CDC conditions.

B. LFP Lithium-Ion Battery Test Results

LFP cells (nominal voltage 3.2 V, rated capacity 104 Ah) showed a greater level of intrinsic safety. Table 2. is a summary of the test results.

Table 2: LFP Battery Test Report

Test	SOC	Key Conditions	Results (Voltage/Capacity Start → End; Max Temp)
Vibration (8h/3 axes)	100%	Manufacturer spec	3.62V/104.22Ah → 3.62V/104.22Ah
Mechanical Shock	100%	Manufacturer spec	3.64V/104.16Ah → 3.64V/104.16Ah
Crush	100%	Max 19.22kN	OCV 3.61V (pre/post), 25.2°C

Temp. Cycling (30 cycles, -20°C to 65°C, BEV profile)	80%	w/ electrical operation	3.11V/85.06Ah → 3.07V/84.96Ah
External Short Circuit (<5mΩ, 10min)	100%	RT	OCV 3.64V, 85.2°C
Overcharge (1It to 2x max V)	100%	104A constant	OCV 3.62V, 61.3°C (tripped at 7.3V)
Forced Discharge (1It, 90min)	0%	104A	2.65V start, 74.7°C

Observations:

- LFP cells demonstrated better thermal stability with no ignition events under the test conditions.
- Voltage and capacity retention were consistent across cycles.
- Lower energy density is offset by enhanced safety.

C. Comparative Analysis: NMC vs LFP Cells

Table 3: NMC vs LFP Comparison

Feature	NMC Battery (Nickel Manganese Cobalt)	LFP Battery (Lithium Iron Phosphate)
Chemistry	Nickel, Manganese, Cobalt cathode	Lithium Iron Phosphate cathode
Nominal Voltage	~3.7 V	~3.2 V
Energy Density	High (180-250 Wh/kg)	Moderate (120-160 Wh/kg)
Weight & Size	Lighter and more compact	Bulkier and heavier
Safety	Moderate; requires complex battery management	High; thermally stable and less prone to fire
Thermal Runaway Temp	~210°C	~270°C
Cost	Higher due to cobalt and nickel	Lower; uses abundant materials
Environmental Impact	Higher; concerns about cobalt mining	Lower; more environmentally friendly
Cycle Life	Shorter (~1,000-2,000 cycles)	Longer (~2,000-5,000 cycles)
Capacity Degradation	Faster (5%-8% capacity loss per year)	Slower (3%-5% capacity loss per year)
Low-Temperature Performance	Better; retains capacity in cold	Poorer; reduced capacity and efficiency below 0°C
Charging Speed	Faster charging, higher power density	Slower charging
Applications	Long-range EVs, fast charging, portable devices	Stationary energy storage, city EVs, cost-sensitive uses

NMC cells excel in terms of energy density and compactness, but need to be better monitored to prevent them from thermally running away. LFP cells are safer for high current applications and longer term cycling with lower risk of fire.

D. Thermal Runaway and Safety Observations

- NMC Cells:
 - Voltage collapse and current instability noticed on overcharge.
 - Thermal runaway level reached quicker than LFP cells.
- LFP Cells:
 - Increased internal thermal tolerance.
 - No disastrous failure under identical test conditions.
- Preventive Measures Effectiveness:
 - Real-time temperature alerts, low voltage cutoffs and predictive BMS successfully prevented cell failure.
 - Plexiglass barriers and thermal imaging were added for extra protection.

V. CONCLUSION

This research was conducted in order to investigate the thermal, electrical and operational behaviour of the high-capacity lithium-ion cells and subject them to controlled Charge-Discharge-Charge (CDC) testing. The experimental analysis of the two types of cells Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP) showed that both cells have considerable discrepancies in performance and safety. In comparison to LFP cells, NMC cells were safer in terms of energy density but were fairer in terms of thermal stability at normal conditions and consequently more susceptible to voltage collapse and thermal runaway. The CDC tests proved rather useful to detect the initial red flags which encompassed rapid voltage drops, current instability and local heating and analysis of failure logs assists in providing an insight into root causes which included internal short circuits and overvoltage cases. Up to the multiple safety controls (measuring real-time temperature, voltage levels, predictive Battery Management System (BMS) analytics, and physical barriers) were useful to minimize the danger and eliminate catastrophic failures. The comparison analysis has revealed that LFP chemistry may be adapted appropriately to be utilized in cases that require high safety and long cycle lifetime, and the NMC cells may be utilized to the applications that must be of high energy density and that will demand strict control. Overall, the identified methodology provides a good solution to the testing of industrial batteries and can be used to identify instability in the initial stages, which will contribute to raising the reliability level and acquiring preventive measures. The research can further be focused on integrating machine learning-based predictive control, developing automated adaptive control, and testing standards in order to embrace the future electric vehicles and energy storage of the future with the implementation of the hybrid chemistries as well as large-scale battery packs.

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