Size-dependent failure behavior of commercially available lithium-iron phosphate battery under mechanical abuse

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Abstract
Under mechanical abuse, the failure of lithium-ion batteries occurs in various stages, characterized by different force, temperature, and voltage responses, and require in situ measurements for analysis. First, four sizes of commercially available lithium-iron phosphate batteries (LFPB), namely 18650, 22650, 26650, and 32650, were subjected to quasistatic lateral and longitudinal compression and nail penetration tests. The failure, characterized by the voltage drop and temperature rise at the onset of the first internal short-circuit (ISC), was identified by an Aurdino-based voltage sensor module and a temperature measurement module, respectively. The battery failure load and peak temperature at the onset of ISC were found to rely strongly on the battery size. The failure was delayed for small-sized 18650 batteries during lateral compression, unlike in longitudinal compression and nail penetration tests. At the onset of ISC, the temperature rise above the ambient value was different for different LFPBs. It was found to be maximum (36.4°C) for LFPB 32650 under longitudinal compression and minimum (1.5°C) under lateral compression tests among the considered geometries. Further, LFPB 26650 exhibited a balanced thermal behavior during the test. Such thermal response can be sensed timely for effective thermal management of lithium-ion batteries.

KEYWORDS
battery failure, compression, internal short circuit, lithium-ion battery, lithium-iron phosphate battery, mechanical abuse, mechanical integrity

1 | INTRODUCTION

Use of batteries is increasing day by day in our daily life, starting from the alarm clock to laptops, smart phones, electric vehicles (EVs), and so on. Moreover, a rapid switchover to battery-based clean transportation technologies from oil-based transportation is one of the possible solutions to mitigate air pollution. In most cases, the use of lithium-ion batteries (LIBs) is already commercialized because of their high energy density. However, they have a greater tendency to catch fire and explode when subjected to undesired loading such as in case of an EV crash or overheating due to operating conditions beyond the design basis, leading to serious consequences. Growing cases of fire in EVs due to battery failure1-4 have raised an important safety concern among the EV manufacturers towards developing stringent safety standards for EV batteries, such as GB/T 31485-2015 developed by China.5,6 Likewise, UL 2580, USABC, Freedom CAR of USA, KMOVSS 18-3 of Korea, UN/ECE-R100.02 of the European Union, and AIS-048 of India have been developed.7 However, the dynamics of failure of LIBs are still not thoroughly understood. For this reason, safety assessments of batteries are much needed for time-to-time revisions in the safety standards.

According to recent evidence,8 lithium-iron phosphate batteries (LFPBs) have a safer operation compared to lithium cobalt oxide batteries (LCOBs) and lithium manganese oxide batteries (LMOBs or
NMCs). Because of their advantages of greater thermal stability and crash safety, LFPBs are gaining the attention of EV manufacturers. Therefore, nowadays, significant research activities are seen focusing on the safety testing of batteries under mechanical and thermal abuse loadings. Commonly, mechanical abuse tests involve the prediction failure due to ISC. Such temperature heterogeneity is common in cylindrical batteries during both discharging and charging conditions. The extent of temperature rise is largely dependent on the charging or discharging rate (expressed as the C rate), which is a measure of the charge and discharge current with respect to the nominal capacity of a battery. In other words, a battery with capacity of 1 Ah can supply 1 A current for 1 h at a discharge rate of 1 C. In the case of discharging/charging at a higher C rate, the heat generation is high, necessitating the use of an efficient cooling system. Thakur et al.23 have discussed the battery thermal management system (BTMS) with a cold plate, composite phase-change materials (PCMs), hybrid BTMS, and some recent variations of BTMS for fast charging conditions. For both the charging and discharging conditions, batteries with PCM-based cooling systems24–27 were found to have improved performance. Although the control of such cooling system is difficult because of the complex heat generation phenomenon, the fundamental equation of energy, continuity, and momentum28 are used in simulating the thermal response of batteries. These studies revealed the thermal response of LIBs under different discharging/charging conditions, while Braga et al.29 discussed the cell degradation phenomenon and gas release during thermal runaway.

The finding of the present work also raises a question about which battery size is suitable for what type of EVs, wherein power and energy density requirements are appropriately met with reduced risk of failure. In hybrid EVs, different sizes of cylindrical shells are being used depending on the power and energy requirements: for example, the Tesla base model uses LIB 18650, while the Tesla model 3 uses LIB 21700 having a higher capacity.30 The specification and application of batteries of different sizes are listed in Table 1.

Despite being designed as per strict safety standards, several cases of fire and explosion of hybrid EVs have been witnessed, prompting the identification of the possible reasons of such incidents. Certainly, the thermal response of batteries is a major cause of failure, which is different for different-sized batteries.31–33 It is well known that the battery size is proportional to stored energy, and hence its energy release rate is different. Consequently, risk of thermal runaway is more for bigger batteries. These arguments necessitate the study of the size-dependent failure of LIBs. To the best of our knowledge, the size-dependent failure behavior of cylindrical LFPBs under mechanical abuse has not been reported yet. Since batteries are available in many shapes and sizes, and the design of their internal components differ, a postmortem analysis of a pristine battery is needed for a comparative assessment of the safety features provided.

In this context, the present work reveals the size dependence of LFPBs, focusing on thermal response under mechanical abuse conditions. The battery chemistry governs the energy density and capacity; however, the geometry (which includes shape: cylindrical, prismatic, and pouch; and size: 18650, 22650, 26650, 32650 for cylindrical batteries) plays an important role in its safe operability. Considering the significance of size, the present work aims to analyze the effect of the
dimensions of various components of LFPBs. To analyze the effect of the dimensional parameters, postmortem analysis of four sizes of pristine LFPBs (18650, 22650, 26650, and 32650) is conducted. The structural design of the internal components is ignored, as well as morphological analysis, which is mainly performed for aged batteries. Moreover, size dependences are analyzed by considering batteries of different diameters and comparing the failure load and temperature rise at the initiation of ISC. The mechanical behavior of LFPBs is segmented into different stages when subjected to loading, revealing its layered and multicomponent structure.

### TABLE 1 Specifications of batteries (manufacturer's data).

| Model     | IFR 18650 | IFR22650 | IFR2650 | IFR32650 |
|-----------|-----------|-----------|---------|-----------|
| Capacity (mAh) | 1500      | 2000      | 3000    | 5000      |
| Nominal voltage (V) | 3.2       | 3.2       | 3.2     | 3.2       |
| Charging voltage (V) | 3.65      | 3.65      | 3.65    | 3.65      |
| Anode      | Graphite. | Graphite. | Graphite| Graphite. |
| Cathode    | LiFePO₄   | LiFePO₄   | LiFePO₄ | LiFePO₄   |
| Electrolyte material | Carbonate-based | Carbonate-based | Carbonate-based | Carbonate-based |
| Continuous maximum charge current | 1C 5A | 1C 5A | 1C 5A | 1C 5A |
| Continuous maximum discharge current | 3C 5A | 3C 5A | 3C 5A | 3C 5A |
| Width (mm) | 18        | 22        | 26      | 32.2      |
| Height (mm) | 65        | 65        | 65      | 65        |
| Weight (g) | 40        | 60        | 85      | 140       |
| Operating temperature range (°C) | Charge: 0–45 | Charge: 0–45 | Charge: 0–45 | Charge: 0–45 |
| Application | For future Tesla cars, E-bikes, LED flashlights | Car, E-bikes, wheelchair | High-powered LED flashlights | Three-wheelers, high-power LED flashlights |

**FIGURE 1** (A) Picture of LFPB 18650, 22650, 26650, and 32650P. (B) Parts of LFPBs (components of safety valve, copper foil terminal strip, seal, casing, jellyroll, negative terminal, negative terminal plate, outer covering of cell). (C) Control pin found only in LFPB 32650.

2 | EXPERIMENTAL

Postmortem analysis of pristine LFPBs (SONY: IFR18650, IFR22650, IFR26650, and IFR32650) was conducted to examine the internal structure and components (Figure 1 and Table 1). Subsequently, mechanical abuse testing was carried out with pristine samples of LFPBs of each size. In order to minimize experimental uncertainties, the measurements were done using calibrated instruments in the laboratory environment. The thermocouple and other connections were ensured to be intact during the test. The abuse tests were conducted.
for three sets of samples of LFPBs 18650 and 26650, while samples of other sizes were tested with the same configuration for similar loading situations.

### 2.1 Postmortem analysis

The postmortem analysis performed in the present work includes the disassembling of pristine LFPBs, identification of the battery components, measurements of the key dimensions of the subcomponents, and the calculation of specific density, as reported in the literature. The procedure involved discharging of the batteries to zero SOC and removing the nonconductive polymer covering from the outer casing. The subsequent procedure included the careful cutting of the outer casing near the positive and negative terminals using a hacksaw blade. The standard safety protocols were followed during all experiments. The disassembling of LFPBs can be dangerous because of the possibility of short-circuiting and release of harmful electrolytes or fumes. Therefore, protective gloves and masks were used while performing it. Once the cell was opened, the spiral wound jellyroll was extracted from the casing after the removal of the positive terminal plate and dismantling the components of the safety valve. After complete disassembly, the various components were identified, as shown in Figure 1A, B.

### 2.2 Quasistatic mechanical testing

Quasistatic lateral compression, longitudinal compression, and nail penetration tests were carried out to explore the mechanical behavior of the individual battery. The tests were performed in a calibrated universal testing machine (Werkstoffprüfmaschinen, Germany) of 40-ton capacity. The tests for lateral compression, longitudinal compression, and nail penetration tests were conducted on LFPBs as shown in Figure 2A-D. Nail penetration tests of LFPBs 18650 and 22650 were conducted in a semiclosed fixture, as shown in Figure 2C. To ensure the safety of the operator from the high-capacity LFPBs (26650 and 32650), the tests were conducted in a completely closed fixture. The fixture included a hollow cylinder of thickness 4 mm and diameter 34 mm to hold the LIB inside it. A through hole was provided on the fixture for holding the nail in place, as shown in Figure 2D. The compression and nail penetration tests were conducted at a loading speed of 5 mm/min until the voltage dropped to zero and the temperature started rising. The temperature was measured by using a K-type thermocouple (accuracy ±1.5°C as per IEC 584-2). The thermocouple was attached to the surface of a battery using a Kapton tape at the positive terminal, which shows a higher temperature than the negative terminal. The battery samples were connected to an Arduino-based voltage module (MAX6650) and a temperature module (MAX6675) (Figure 2E, F) for the in situ recording of voltage and temperature data.
using the Arduino-UNO, respectively. The voltage and temperature modules were calibrated using a multimeter (DT830D) and a noncontact infrared thermometer (IT-1520), respectively. The voltage, temperature, displacement, and load data were recorded during lateral and longitudinal compression and nail penetration tests. The experiment was performed with a protective transparent shield of acrylic material to protect the test equipment and the operator.

### RESULTS AND DISCUSSION

The dimension of key components and subcomponents were measured using a digital micrometer (for thickness), a digital vernier calipers (for width), and a measuring tape (for length) and are listed in Table 2. It was found that the same components were present in all the samples except for an additional central pin in LFPB 32650. The hollow central pin facilitates the venting of fumes through it to prevent short-circuiting and separator burnout.

The safety valve assembly included some subcomponents such as a positive temperature coefficient (PTC) device, a plate with safety vents, a positive terminal plate, and a gasket seal. The jellyroll, which includes an anode, cathode, and two layers of a polymeric porous membrane separator, is the most essential part that stores the energy. The active anode material, namely graphite, was found to be deposited on both the sides of copper current collector surfaces. The active cathode material, that is, LFP coating, was seen on both sides of an aluminum current collector. A separator that is permeable to ionic flow was found between the electrodes. The ions travel to the anode from the cathode during the charging process, and vice versa during discharging through the separator. The measurements for the subcomponents and the calculated specific density of the LFPBs are listed in Table 2.

The dimensions of the subcomponents of LFPBs were measured to understand their contribution to the energy storage capacity. The capacity of batteries depends on the volume of active materials on electrodes, that is, graphite on copper foil (Figure 3A) and LFPs on aluminum foil (Figure 3B), and the total volume of LFP and graphite together (Figure 3C). The volume of LFP is highest in LFPB 32650 but the ratio of LFP to graphite deposited on the copper and aluminum foil, respectively, is maximum for LFPB 26650 (i.e., 5.85) and minimum for LFPB 18650 (i.e., 0.61). It can be seen from the plot that, among all the LFPBs considered, the least amount of copper was used in 26650 cells with 3000 mAh capacity. Although a higher amount of copper is used, the capacity of 18650 and 22650 are 1500 and 2000 mAh, respectively, which are lower than the capacity of LFPB 26650 (Figure 3). It indicates that the battery capacity is not solely dependent on the amount of LFP but also depends on the ratio of LFP and graphite, which is an important parameter governing the capacity. Also, considering the aspects of effective utilization of materials toward ensuring sustainable development in the field of energy storage, such findings may help in developing LFPBs with reduced copper.

The findings from the postmortem analysis showed a direct correlation between the volume of active materials and the capacity, which governs the size of the battery. It may subsequently affect the failure behavior of each LFPB considered in the present investigation. To validate that, an in-depth investigation of the size-dependent failure behavior of LFPBs subjected to lateral and longitudinal compression tests and nail penetrations tests was carried out and characterized by the onset of ISC. One can easily visualize the failure, evident in the form of fumes released, as shown in Figure 4A–D. The fumes may
contain toxic lithium hexafluorophosphate (LiPF$_6$), which evaporates and immediately converts into short-lived, toxic hydrogen fluoride in the presence of moisture. According to previous reports, the rate of release of hydrogen fluoride for cylindrical LFPBs compared to several other battery chemistries was found to be 24 mg/Wh at 100% SOC in the case of the fire test. Though the present work does not include an estimation of the rate of release of fumes, the rate of release was visually distinct after the event of a short-circuit at a time delay of 1–3 s (recorded during the tests) between the release of fumes and onset of short-circuit in the lateral compression and nail penetration tests. In the case of longitudinal compression, a time delay of 5–8 s was observed. Such delay in the release of fumes increases the risk of

FIGURE 3  Active materials in LFPB 18650, 22650, 26650, and 32650. (A) Volume of graphite on copper foil. (B) Volume of lithium-iron phosphate (LFP) on aluminum foil. (C) Total volume with active materials of LFP and graphite (on aluminum and copper foil both).

FIGURE 4  Release of fumes at the ISC during mechanical abuse tests: (A) lateral compression, (B) longitudinal compression, and nail penetration with (C) semi-closed and (D) fully closed sample fixture. (E) Representation of compaction of jellyroll in lateral compression, (F) bending and buckling of jellyroll in longitudinal compression, and (G) localized compaction in nail penetration.
Figure 5 Variation of force, voltage, and temperature with displacement: for lateral compression in (A) 18650, (B) 22650, (C) 26650, (D) 32650; for longitudinal compression in (E) 18650, (F) 22650, (G) 26650, (H) 32650; and for nail penetration (I) 18650, (J) 22650, (K) 26650, and (L) 32650.
explosion too and should be avoided. It should be noted again, that the tests were conducted by following the safety procedure, keeping the place of the test well ventilated with operating exhaust systems, and wearing FFP3 respirator masks. Figure 4A shows the abused sample corresponding to lateral compression of LFPB 18650 displaying rapid release of fumes compared to that observed in Figure 4B for longitudinal compression of LFPB 32650. This indicates a high rate of chemical reactions occurring in the case of lateral compression due to the involvement of the full length (i.e., 65 mm) of active materials on the electrodes in the short-circuit event compared to that occurring in longitudinal compression. Such rapid release of fumes and electrolytes was facilitated by the provision of vents in the samples. On the other hand, the rate of release of fumes and electrolytes in the case of nail penetration tests was less (Figure 4C, D) due to the short-circuits at smaller regions or localized spots under the nail tip. Figure 4E–G illustrates the area of active material involved during the compression tests. To avoid the chance of battery explosion due to the high rate of exothermic chemical reactions during short-circuiting, blockage of the vents should be avoided. The chance of battery explosion is reduced in lateral compression and nail penetration, as the release of fumes and electrolytes is facilitated by the presence of vents and holes due to nail penetration, which are blocked because of the machine cross-head in case of longitudinal compression.

The in situ measurement of applied force, voltage, and temperature data with the cross-head displacements during the quasistatic abused loading were recorded and are illustrated in Figure 5. The load–displacement curve is used to identify the failure load, which is considered as the load at the instant of voltage drop due to mechanical failure or rupture of the jellyroll during ISC. The load versus displacement can be segmented into four stages as follows: (i) stage I represents the compression of the cell tab and casing of the battery till the jellyroll and cell tab contact is developed; (ii) stage II shows the onset of jellyroll compression after casing compression is complete; (iii) stage III denotes the compaction stage wherein the jellyroll is compressed and bent leading to buckling and short-circuiting at the spot of the contact point; (iv) last stage, stage 4, marks the complete failure of battery after severe or hard short-circuit. Since the present work focuses on the onset of failure of LFPBs, the load versus displacement curve shows evidence of three stages only. The onset of the short-circuit, evident as a drop in voltage, which is called a soft short-circuit, becomes severe if further compaction or loading is continued, resulting in a hard-short circuit. Therefore, the first event of voltage drop can be considered as a reference instant of time that can be used as an early warning system to control the catastrophic failure leading to thermal runaway. Referring to Figure 5A–D, for lateral compression, the failure load for LFPBs 18650, 22650, 26650, and 32650 is found to be 44.00, 31.88, 12.78, and 6.68 kN, respectively. It implies that the smaller the size, the larger the failure load for the considered LFPBs. This leads to greater compaction of the jellyroll, that is, higher displacement, resulting in a higher temperature at the onset of ISC.

Referring to Figure 5E–H, for longitudinal compression, the failure load for LFPBs 18650, 22650, 26650, and 32650 is found to be 2.92, 7.76, 11.44, and 31.24 kN, respectively. It shows that, the smaller the size, the smaller is the failure load for the considered LFPBs. Under
longitudinal compression, the load acted along the axis of the LFP considered. This leads to the initial bending of the jellyroll with eventual buckling (Figure 4F). Such buckling deformations cause a smaller area of direct contact between the electrodes in a small battery (LFPB 18650), resulting in the lowest temperature rise at the onset of ISC compared to LFPB 32650, which displayed the highest temperature rise. On comparing the load–displacement curve for lateral compression, LFPB 32650 shows a sudden drop in failure load in stage III. Such a drop in load (Figure 5G) can be attributed to the sudden compaction of the hollow central pin, which is found only in LFPB 32650.

FIGURE 6  Failure load, displacement, and temperature at the onset of short-circuit corresponding to (A–C) lateral compression, (D–F) longitudinal compression, and (G–I) nail penetration. (J) Pictures of failed LFPB samples after nail penetration (S1–S4), lateral (S6–S9), and longitudinal compression (S10–S13) tests.
The hollow central pin provides the passage for gaseous products/fumes to the vent. Additionally, it provides buckling strength to the jellyroll displaying a higher failure load as in Figure 5H, corresponding to longitudinal compression. These results suggest that there should be an optimal dimension of the battery such that the chances of thermal runaway due to mechanical abuse can be controlled. Referring to Figure 5I–L, in the case of nail penetration tests, the failure load for the onset of ISC is very high for LFPB 32650 compared to the other battery sizes. Also, the failure behavior of the LFPBs shows that the nail penetration depth required for the onset of ISC decreases with the decrease in the size of the battery for the considered LFPBs.

According to the literature, the safe operating temperature of LIBs lies in the range 20–60°C during the discharge process. Figure 5 shows that there is an increase in surface temperature upon increasing the loading. The temperature rise is due to the exothermic chemical reactions inside the LFPBs during ISC. Temperature also rises as a result of Joule heating; hence the combined heat due to the Joule heat and exothermic chemical reaction post short-circuiting (soft and hard) is the reason for further rise in temperature. Both soft and hard short-circuits are phenomena wherein the flow of charge takes place between the battery electrodes through the zero resistance path that is created because of failure of the battery separator.

Soft short-circuit involves only a few electrode layers that come into direct contact with each other in comparison to the hard-short circuit. Consequently, the drop in voltage and temperature rise are different at these short-circuit cases. Involvement of more layers of electrodes during short-circuit results in a large amount of heat generation, which can lead to complete failure due to uncontrolled chemical reaction. Such cases can fall under the category of hard-short circuit, leading to excessive temperature rise which may result in thermal runaway and fire or explosion. This temperature rise should be kept within the safe limit to prevent thermal runaway, and the battery thermal management systems should be designed accordingly to respond to such undesirable events. Soft short-circuit is a triggering event for thermal runaway, and therefore the present test results can be used to develop appropriate methodologies for early warning systems to detect failure. For better clarification, the size dependences of commercial LFPBs considered in the present work are analyzed using Figure 6 by a comparative assessment of the failure behavior. Figure 6A shows decreases in failure load with an increase in the size of the LFPBs in the case of lateral compression. Referring to Figure 6B, C, for LFPB 18650, the temperature rise is about 38.75°C, which is slightly higher than the optimum temperature range (15–35°C) for LIB in the literature. Further, the rise in temperature due to the short-circuit is delayed by the decrease in the diameter of the LFPBs for the lateral compression test. The delay in temperature rise implies lesser heat generation rate. Such temperature rise data therefore becomes important for faster heat diffusion and effective thermal management. Figure 6D shows an increase in the failure load with the increase in the size of the LFPBs in the case of lateral compression. Referring to Figure 6E, F, the rise in temperature starts earliest for the LFPB 18650 cell and gets delayed with the increase in diameter of the LFPBs in case of longitudinal compression. Referring to the results of nail penetration tests in Figure 6G, the value of the failure load for LFPB 32650 is 0.72 kN, which is the highest among the batteries of various sizes. Referring to Figure 6H, I, the short-circuit temperature is almost the same for LFPBs 18650 and 22650. A lower short-circuit temperature is noticed for larger LFPBs as observed for 26650 and 32650 in comparison to 18650 and 22650, with the earliest short-circuit in 18650 compared to the other larger LFPBs subjected to nail penetration tests.

The failed samples after the mechanical abuse tests are shown in Figure 6J. The formation of the hole on nail penetration-tested LFPBs (Figures 6J and S1–S4) was visible in all the tested samples. Rings formed (Figure 6J and S13) in LFPB 18650, indicating the cause of ISC as due to buckling in longitudinal compression tests. During longitudinal compression testing of LFPB 26650, there was a sudden rupture and tearing of the casing (Figures 6J and S11), leading to a mild explosion due to the blockage of the vent by the cross-head. A high-temperature-resistant tape was used to avoid malfunctioning/disconnection of the wire soldered to the LFPB samples during tests. The subsequent tests were conducted after creating holes in the thermal tape, keeping the vent space open during the tests.

4 | CONCLUSION

The present work included the postmortem analysis of pristine cells. It was noted that a central pin was provided additionally in LFPB 32650 as an extra safety measure to facilitate the passage to gas/fumes from the negative to the positive terminal in case of a thermal runaway. Other important conclusions of the present work highlighting the size dependences on the failure behavior of LFPBs considered are as follows:

1. Failure load decreases with an increase in the diameter of the LFPBs for lateral compression tests; alternatively, it increases with an increase in size for longitudinal compression tests. During the nail penetration test, the failure load is maximum for LFPB 32650 among the batteries considered.
2. The onset of internal short-circuit delays with an increase in diameter of the batteries for longitudinal and nail penetrations tests, while it occurs earliest in the case of large batteries, for lateral compression tests.
3. The temperature rise at the onset of short-circuit is different for different battery sizes. It is found to be maximum, that is, 36.4°C (or temperature reached to 64.4°C), for LFPB 32650 in case of longitudinal compression and minimum, that is, 1.5°C (or temperature reached 29.5°C), for lateral compression. On comparing the values of the temperature rise at the onset of short-circuit, a balanced thermal behavior of LIB 26650 is revealed for all mechanical abuse conditions considered.
4. A time delay of up to 3 s between the release of fumes and the onset of the short-circuit was observed in lateral and nail penetration tests, while it was up to 8 s in longitudinal compression tests. An increase in the delay in the release of gas/fumes increases the
risk of gas accumulation and subsequent explosion. The risk of explosion also increases if vents are blocked, which was seen in the case of LFPB 26650, wherein the vent was blocked due to the Kapton taping used to keep the thermocouple in position during the test.

These test results may have significant implications for the development of testing standards for batteries and early failure detection systems for battery packs towards improving the safety of EVs.

** NOMENCLATURE **

| Abbreviation | Description |
|--------------|-------------|
| AIS          | Automotive industry standard |
| BTMS         | Battery thermal management system |
| CAR          | Cooperative Automotive Research |
| EV           | Electric vehicle |
| GB/T         | Guobiao standards |
| IFR          | International Federation of Robotics |
| ISC          | Internal short-circuit |
| LCOB         | Lithium cobalt oxide battery |
| LFP          | Lithium-iron phosphate |
| LFPB         | Lithium-iron phosphate battery |
| LIB          | Lithium-ion battery |
| LMOB or NMC  | Lithium manganese oxide battery |
| PCM          | Phase-change material |
| PNE          | Potential of negative electrode |
| PTC          | Positive temperature coefficient |
| SOC          | State of charge |
| UBHC         | Upper bound of heating current |
| UL           | Underwriters Laboratories |
| UN/ECE       | United Nations Economic Commission for Europe |
| USABC        | United States Advanced Battery Consortium |
| mAh          | Milliampere-hour |
| Ah           | Ampere-hour |
| °C           | Degree celsius |
| mm           | Millimeter |
| G            | Gram |
| V            | Volt |
| cm           | Centimeter |
| mm²          | Cubic millimeter |
| Wh/kg        | Watt hour per kilogram |
| mg/Wh        | Milligram per watt hour |
| kN           | Kilo newton |

**AUTHOR CONTRIBUTIONS**

Vishesh Shukla: Conceptualization (equal); data curation (equal); investigation (equal); methodology (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). 
Ashutosh Mishra: Conceptualization (equal); data curation (equal); methodology (equal); project administration (equal); resources (equal); supervision (equal); validation (equal); visualization (equal); writing – review and editing (equal).
Jagadeesh Sure: Resources (equal); validation (equal); visualization (equal); writing – review and editing (equal).

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The authors declare no conflicts of interest.

**DATA AVAILABILITY STATEMENT**

Data will be made available upon readers’ request.

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