Reliability of Cylindrical Li-ion Battery Safety Vents

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ABSTRACT Cylindrical Li-ion batteries (cells) typically have safety vents in the positive terminal to enable the release of gases that build up inside the battery and thus help reduce the effects of thermal runaway, including fire and explosion. However, the vents are not always effective, and it is critical to understand why. This paper overviews various vent designs and presents two case studies of vents in cylindrical Li-ion batteries that failed to operate properly. The first case study concerns a Sony VCT5 18650 Li-ion battery in which thermal runaway caused the cylindrical casing (can) to rupture. The second case study involves an Ampking 20700 Li-ion battery in which thermal runaway caused side-wall rupture of the casing. In both cases, the vents did not function as intended. Computed tomography (CT) scanning was used to investigate the internal structure of the battery to assess the failure mechanisms of the failed vents. These cases raise concerns about the efficiency, reliability, and safety of some current vent designs.

INDEX TERMS Vent failure, explosive failure, cylindrical Li-ion battery, CT scan, thermal runaway.

I. INTRODUCTION Li-ion batteries (cells) are widely used for energy storage owing to their high energy density and high capacity. Cylindrical cells, such as the 18650s, are some of the most economical, high-power Li-ion batteries and are widely used in appliances, e-cigarettes, power tools, and electric vehicles [1]. However, numerous fire and explosion incidents involving Li-ion batteries have raised safety concerns [2]–[5]. Furthermore, catastrophic battery accidents resulting in thermal runaway have increased with the growing popularity of battery-operated products.

Thermal runaway is a phenomenon in which there is a continuous, uncontrollable temperature increase inside a Li-ion battery. Thermal runaway can be precipitated by manufacturing defects within the battery or by external electrical, mechanical, and thermal abuse, including overheating, overcharging, short circuit, and object penetration [6]–[9]. In all these scenarios, once internal heating reaches a threshold temperature, the battery will continue to generate heat uncontrollably due to internal exothermic reactions [10]. During thermal runaway, the increased temperature also causes the generation of gases, and the increase in internal pressure can lead to battery rupture, fire, and explosion. Fu et al. [11] reported that the maximum surface temperature can reach up to 943\textdegree for a fully charged 18650 battery.

To prevent thermal runaway, companies incorporate various safety devices into Li-ion batteries, including positive temperature coefficient (PTC) thermistors, current interrupt devices (CIDs), and safety vents [12], [13]. The first two devices, PTC thermistors and CIDs, are fuse-like mechanisms [12]. A PTC thermistor reduces the flow of electrical current when an external short occurs. The PTC thermistor’s resistance increases when the temperature increases due to an external short circuit. In this way, the battery current and the corresponding ohmic heating effect is greatly reduced. The PTC thermistor is resettable; if the battery temperature decreases back to its normal range, the PTC thermistor will revert to the low resistance state and thus allow the battery to operate normally. However, the PTC thermistor cannot prevent an internal short circuit, such as one caused by an internal defect [14]. Moreover, a PTC thermistor...
alone may not stop thermal runaway propagation in a battery pack, which contains multiple cells in series and/or parallel [15], [16]. In these cases, if the series-connected cells are shorted, the first PTC thermistor that trips in the series configuration can induce a voltage drop that exceeds its voltage rating and may result in failure. Once the first PTC thermistor fails in a large series of cells, the short can transmit this failure and cause the next PTC thermistor to fail until all the cells short [15]. Fire and explosion can then occur.

A CID permanently cuts the electrical current and places the battery into an open circuit state. The CID can be activated by pressure, temperature, or a circuit monitoring the battery status. In most 18650 cylindrical batteries, the activation method is pressure, and the critical pressure for a CID is around 1000 kPa [15], [17]. Once this threshold value is reached, the structure of the CID is destroyed and the battery can no longer operate. While a CID is a reliable method for single cells, for a battery pack having voltages over 20 V, Augeard et al. [15], [18] found that the CID opening can generate and maintain an arc that could result in thermal runaway. NASA researchers [16] reported the CID arcing could be ignited at 55 V and 110 V for Moli batteries and Sony HC batteries, respectively. However, no arcing is possible at 20 V. Compton defines the term arc as “discharge of electricity, between electrodes in a gas or vapor, which has a voltage drop at the cathode of the order of the minimum ionizing or minimum exciting potential of the gas or vapor.” Augeard et al. [15] found 20 V is the critical value for a sustained arc. Since a single cell 18650 voltage is less than 5 V, a sustained arc should not occur.

Safety vents are introduced into Li-ion batteries to decelerate the thermal runaway process and prevent explosion by releasing the gases that arise from the exothermic reactions in the battery [19], [20]. Zhang [21] reported that thermal runaway could be avoided if the cell vent opened immediately when some threshold level of heat was generated inside the cell. Tobishima and Yamaki [22] reported that the venting depends on the overcharge rates, but noted that a battery casing could rupture if the vent does not work properly. In their experiment, the safety vent did not work, and the battery exploded when it was overcharged to approximately 4.5 V at 2C. In that instance, the negative cap housing opened simultaneously with the safety vent opening due to the greatly increased temperature resulting from Joule heating.

Safety vents are recommended for Li-ion batteries by standards such as IEEE 1725-2011 for rechargeable batteries for cellular telephones [23]. Pouch cells usually use sealed electrolyte injection holes as the vent [24]. Some coin cells have vents around their circumference [25]. In the 18650 cylindrical cell, the vent is included in the battery cap subassembly. For the proper working of the safety vents, gases must be quickly expelled from the battery in the initial stages of thermal runaway, and the vents should not be clogged by any materials ejected from the battery during thermal runaway [26].

A key question is under what conditions will safety vents operate improperly. This paper examines the issues with vents and presents two case studies—an exploded Sony 18650 VTC5 battery and a side-wall-ruptured Ampking 20700 battery. The paper is organized as follows. Section II introduces vent mechanisms and structures. Section III presents thermal runaway test results and the CT scan results of the exploded 18650 battery. Section IV presents the case study of the exploded 20700 battery with side-wall rupture. Conclusions and recommendations for vent design and testing are presented in Section V.

II. VENT MECHANISMS IN CYLINDRICAL Li-ion BATTERIES

The safety vent in a cylindrical Li-ion battery is installed to decelerate thermal runaway and prevent a battery from rupture and explosion [27], [28]. Thus, the venting should occur at the very initial stages of thermal runaway in order to expel enough generated gases, decelerate thermal runaway, reduce the internal pressure, and prevent an explosion.

The typical vent design involves a structurally weak point in the device that allows an opening to occur upon conditions that might lead to or indicate the occurrence of thermal runaway [27], [29]. Figure 1 shows a typical vent design for a cylindrical Li-ion battery [30]–[32] based on some early patents. As noted, the venting system in cylindrical batteries usually contains three components: the positive terminal, a top/vent disk with groove (scoring or circular arc shape), and a bottom disk layer. The holes on the positive terminal are premade through-holes that allow the flow of gases/liquids. The top disk is the boundary between the battery’s internal structure and the external atmosphere. The top disk blocks the gas releasing pathway, until the pressure difference applied on the top disk is sufficient to break an opening. The groove provides a localized stress concentration and will fracture at a design-for (threshold) pressure [33], allowing gases to escape.

An effective vent design should allow gas to be rapidly expelled from the battery [29]. If the vent does not open in time, thermal runaway will occur. If the vent opening is not big enough to allow the pressure to be adequately...
relieved and/or the vent becomes clogged, the internal pressure will keep increasing and lead to battery rupture and an explosion [27], [35].

III. CASE STUDY OF SONY 18650 SAFETY VENT

This section presents a case study of a commercial Sony 18650 VTC5 2.6-Ah, 3.6-V graphite/NMC (LiNiMnCoO2) Li-ion 18650 battery, in which the vent did not properly operate, resulting in the rupture (explosion) of the battery casing. The cell was fully charged using a constant current/constant voltage (CC/CV) charging profile, which was followed by an open circuit rest for 12 h. The cut-off voltage of constant current charging was 4.2 V, and the discharge end voltage was 2.5 V [36].

To assess the operation of the vent, the battery was placed inside an explosion-proof observation chamber used for thermal runaway experiments (Figure 2). A nickel-chromium heating wire was wrapped around the battery surface to provide a heating source with a constant power of 20.6 W, which was supplied by a DC power source (Agilent E3634A). Two K-type thermocouples were located on the positive and negative sides of the battery to monitor the battery surface temperature. The heating started from room temperature (around 25°C) and was increased until the temperature measured by the thermal couples started to increase more than 1°C/min, which was regarded as the onset of thermal runaway. After the thermal runaway, the heating source was removed when the surface temperature was cooled down to 295°C. The battery voltage was also monitored during the test. An Agilent 34972A data logger was used to record the thermal couple temperature and the battery voltage during the entire experiment.

The temperature and voltage profile during the thermal runaway test is shown in Figure 3. The heating started from room temperature (26.5°C) at 76 s into the test, and the surface temperature increased almost linearly until the vent opened after 520 s. During the experiment, the temperature close to the positive terminal (T1 in Figure 3a) was lower than the temperature near the negative terminal (T2 in Figure 3a).

The first thermal runaway case study was conducted in our lab (the second case study involved a field failure study). The approach involved uniformly wrapping the circumference of the battery surface with heating wire. A constant current was then applied to heat the battery. The heating was verified to be uniformly distributed during the initial heating steps (see Figure 3). Figure 3b is the temperature change trend in the first 20 s, which shows the temperature distribution.

As the temperature increased, localized reactions and early damage to the electrode layers (to be discussed later) inside the battery caused a nonuniformity in the thermal distribution. For example, at 78 s, the temperature was 27.7°C at the negative terminal (T2) and 26.7°C at the positive terminal (T1). The temperature difference was 1°C. But at 92 s, the temperature at the negative terminal was 43.5°C, while the temperature at the positive terminal was 34.1°C. The temperature difference was almost 10°C. At the venting time, the temperature was 157.3°C at the negative terminal and 137.6°C at the positive terminal.

The increased temperature difference between the terminal ends indicates that the temperature distribution of the battery became non-uniform in the axial direction during constant heating. The temperature at the negative terminal was 20°C higher than that of the positive terminal just before thermal runaway. Later, the CT scan showed the battery materials near the negative terminals were expelled. Both findings indicate the initial thermal runaway occurred near the negative terminal. The gases were trapped near the negative terminal of the battery, and burnt layers prevented the safety vent at the positive terminal from properly working.

CT scanning can be used to nondestructively analyze the internal structure of a battery. The brightness in the CT image is related to the materials’ atomic number. Usually, a higher atomic number will lead to higher brightness [37]. Figure 4 presents CT images of the exploded battery from...
FIGURE 4. CT images of exploded Li-ion battery.

different angles. Figure 4a is the top view along the z-axis; Figure 4b is the view along the x-axis; Figure 4c is a front view along the y-axis; and Figure 4d is the 3D image. The bright particles in the images are the solidified metal particles that were melted by the high internal cell temperature. The bright hollow circle in the middle of Figure 4a is the center pin. Some deformed electrode layers and debris are also shown. The dark region in the battery image is associated with the absence of materials or with materials with a low atomic number.

FIGURE 5. Battery terminals after thermal runaway: (a) Images of the positive terminal; (b) Images of the negative terminal; (c) CT cross-section images taken at a depth near the positive terminals of the vent-failed battery after explosion, the dashed yellow line indicates the region of designed venting area; (d) CT cross-section image taken at a depth near the negative terminal.

Figure 5 shows the positive and negative terminals of the exploded battery. The bright particles observed in Figure 5 include melted and re-solidified metal within the battery [40]. In Figure 5c, the bright circle in the middle of the cell is the hollow center pin [38]. The hollow structure of the center pin should provide a pathway to release the gases generated during thermal runaway. That is, the center pin should allow gases generated at the bottom of the cell to reach the top vent on the positive terminal [39], [40].

High temperatures accelerate side reactions in the cell, which speed up gas evolution and pressure build-up inside the cell. If the cell pressure is greater than the threshold value, the vent will open to release gas and ensure battery safety. If the vent fails to operate properly, the increased pressure can cause a rupture in the cell casing. In this study, it was observed that the electrode layers appeared to relocate and stopped the gas flow. Chang et al. [39] also raised the same concern in their patent, where they noted that burned materials accumulated inside the battery and blocked the cap when the vent failed [22], [39]. Therefore, the battery casing can be ruptured under the combined action of the accumulated gas, accumulated burnt debris, the blocked center pin, and the local high temperature.

Figures 5a and 5b show the positive and negative terminals after thermal runaway. The entire battery casing wrapper was burnt. In addition, the positive terminal showed rupture (two holes marked as A and B) in Figure 5(a). Two more holes (marked as C and D) were observed on the negative terminal in Figure 5(b). After the test, the battery mass was 21.4 g, which indicates that almost 22 g of battery materials was ejected out of the cell. That is, almost 50% of the materials inside the battery have been ejected out of the battery.

Figures 5c and 5d are CT cross-section images taken near the positive and negative terminals of the vent-failed battery after the explosion, respectively. If the safety vents worked as intended, the accumulated gases and heat inside the battery should have been released through the vents without causing extra damage. However, two breaches were found on the donut-shaped rim around the vent areas. In Figure 5c, the region inside the yellow dashed circle is the venting area [41]. The black regions (A and B) outside the circle were formed when the active materials burned and burst out of the battery.

Two holes were also observed on the bottom of the battery (C and D in Figure 5d). The two holes were generated by the localized high temperature (where large amounts of debris were observed as shown in Figure 5d), build-up of pressure, and localized rupture of the battery casing (see Figure 5d). The bright debris came from the melted aluminum of the current collectors inside the battery. Hole C (3.92 mm) and the larger hole D (4.59 mm) indicate the points of highest pressure combined with thermal weakening (e.g., a significant reduction in the rupture strength) of the battery casing. This also indicates the reaction was localized. The holes’ formation indicates the venting area is not sufficient to deal with the gas surge. A possible reason is that the safety vent on the top of the battery did not function properly due to clogging by debris. Finegan et al. [20] also observed vent clogging. Furthermore, despite the opening at the center of the jelly roll, the location of the holes indicates thermal runaway, and the generated gases were localized to the cell casing bottom.

Figure 6a is the CT cross-section image of the battery. Figure 6b is the image near the positive terminal along the height direction. The red arrows indicate the gas flow direction. The green arrows point to the space between two
electrode layers, which serve as gas-releasing pathways during thermal runaway. The center pin is inclined to the left of the battery and ‘pushed’ upward following the initial gas flow to the positive cap, hindering further gas release. The dark regions indicate a lack of materials; as previously noted, 50% of the materials were expelled during the explosion. Most electrode layers on the positive side are damaged, while the electrode layers in the middle of the cell are compacted. The deformed electrode layers prevented gases generated at the cell bottom from reaching the top vent during thermal runaway. In this situation, the pressure at the bottom of the battery would further increase.

In Figure 6b, the electrode layers close to the battery casing were less damaged, and the electrode layers on the left side of the positive terminal were generally intact. Along the radial direction of the battery, most of the bright (current collector) debris dispersed throughout the battery. The existence of debris indicates the temperature in the battery center was higher than 660°C (the melting point of aluminum). Moreover, the regions of unburned electrode layers indicate the local temperature was lower than the melting point of the material. Therefore, the thermal runaway process and temperature distribution were non-uniform.

Figure 6c shows a CT scan of the entire 18650 battery after thermal runaway. The spaces between the electrode layers provide a pathway to release gases, especially for gases generated at the cell bottom from decomposition reactions. The positive tabs, which are made of aluminum and have a melting temperature around 660°C, are not observed in Figure 6c; they likely melted and were dispersed throughout the battery. The negative tab, which is usually made of nickel and has a melting point of 1453°C, can be observed, but it has been disconnected from the cell casing. The outer casing of the cylindrical Li-ion battery is made of steel, which has a melting point of 1370°C. Feng et al. [3] pointed out that the internal battery temperature could be 520°C higher than the surface temperature, but even higher temperatures were expected in our study. In Figure 3, the maximum positive terminal surface temperature was approximately 580°C. Thus, the internal temperature at the thermal runaway initiation location can be much higher.

This debris in the sphere shape is seen as “white” dots, which indicates they are metallic particles. According to the temperature measurement, the maximum temperature inside the battery can reach over 800°C [3]. This debris was the solidification particles from melted aluminum during the thermal runaway.

The casing material is steel with a melting temperature of 1370°C. Although the temperature inside the battery was higher than the melting point of aluminum (660°C), it was not high enough to melt the battery casing. However, the mechanical strength of the steel battery casing decreases with increasing temperature. For example, at 700°C, the strength of steel is only 60% compared to its room temperature strength.

The combination of reduced rupture strength of the casing due to the high local temperatures, along with the high local pressure, most likely resulted in the side-wall rupture. The CT scan shows that the bottom of the cell underwent the most degradation, with contents burnt and much of it missing (likely ejected through the ruptured cell), while the materials at the top of the cell remained intact. Gases generated at the bottom during thermal runaway should escape from either the space between the electrode layers or through the center pin up to the top vent. However, the cavities in the lower half of the exploded cell indicate that burnt materials were ejected from the bottom. The clogging and damaging of the positive terminal led to pressure increase and rupture of the cell casing, providing the pathway for releasing the accumulated gas.

IV. CASE STUDY OF AMPKING 20700 SAFETY VENT

This case study investigates a customer’s Ampking 20700 Li-ion battery that exploded during an actual field operating situation. The cylindrical Li-ion battery is larger (20 mm × 70 mm) than the 18650 cylindrical battery (18 × 65 mm). However, both two types of cylindrical batteries have a similar internal structure, and their vent design follows the same principle. In this case, the 20700 battery has no center pin. Therefore, gases generated from the bottom need to travel along the longitudinal direction before they can be released from the top vents.

Figure 7a shows an exploded/ruptured 20700 battery and an unexploded one. The whole area near the hole in the exploded battery bulges, as shown in Figure 7a. This bulge resulted from the pressure build-up inside the battery due to gas generation.

Figures 7b and 7c show cross-section images of the exploded battery, which were taken near the positive and negative terminals. Both the positive and negative terminals are intact, and there is no debris, which means that there was relatively little melting and thus lower temperatures in these regions. In fact, Figure 7b shows no sign of melting or deformation in the positive terminal. The negative tabs can also be observed to be intact based on Figure 7c.

Figures 8a to 8d are CT scan images of the 20700 battery after thermal runaway. Figures 8a and 8b are CT scan images of the positive and negative terminals of the exploded battery. The green arrows show the space between electrode layers where gases could be released. The red arrows indicate the likely direction of the gas flow during thermal runaway. The yellow arrow shows the direction in which the electrode...
layers were compacted. The bright line in the center is the negative tab.

In Figure 8a, it appears that the electrode layers are generally intact (as the unexploded battery). In addition, the spaces between the parallel electrode layers, which provide the pathway for the gases to flow to and be released by the safety vents, appear un-deformed. However, at the negative terminal (Figure 8b), the inter-layer distance of the electrode layers appears to be pressed together. Moreover, Figure 8b shows that the electrode layers have shifted upward, blocking the vents on the positive cap and thus hindering the release of pressure due to gas generation. Finegan et al. [20] have also reported similar electrode shifting during thermal runaway events. Furthermore, the negative tab is observed to be deformed and disconnected from the battery outer casing in Figure 8b.

Figures 8c and 8d show front and cross-sectional views of the side-wall-ruptured sample. In Figure 8c, more bright debris appears on the right side of the battery, especially near the rupture location, compared to other locations. The electrode layers on the negative side are also more compacted than on the positive side. The compacted electrode layers reduce the pathway to release gases from the safety vent on the positive terminal. Furthermore, more debris is observed near the side of the casing where the hole is located. The side-wall swelling and rupture indicate a localized hot spot and concentration of gases and pressure. The dark region in the hole location indicates where electrode materials inside the battery were ejected from the battery [37].

V. CONCLUSION

Safety vents are designed to prevent the rupture (explosion) of batteries by releasing gases and pressure buildup resulting from thermal runaway. However, some vent designs do not always work as intended. This paper presented two case studies that show a battery can still rupture if the generated gases cannot quickly reach the vent, especially if local hot spots and generally non-uniform temperature distributions occur inside the battery and/or the vent becomes clogged.

The case studies involved bottom-rupture 18650 and 20700 side-rupture cylindrical lithium-ion batteries. During thermal runaway, the electrode layers migrated into the venting region and compressed, clogging the vents. The generated debris reduced the effective venting pathway to the vent holes. The mechanical strength of the battery casing was weakened by local heating and plastic deformation. The combination of local hot spots and local pressure buildup resulted in battery casing rupture.

Both of the exploded cylindrical Li-ion batteries indicate safety vent designs are currently not sufficient to prevent the battery explosion and battery casing rupture. The holes on the negative terminal of the 18650 battery indicate that the top safety vent failed to release the gases and heat generated near the battery bottom. The side-wall rupture of the 20700 battery further emphasizes that insufficient venting and local heating can lower the efficiency of venting during thermal runaway.

The ideal safety vent design should avoid clogging from burnt materials. These materials lose their integrity and are thus able to migrate within the cell and clog the vents during thermal runaway. Since safety vents are located on the battery cap, it is necessary to guarantee that gases generated from the bottom of the battery can quickly reach the vent. Furthermore, the battery casing should retain enough mechanical strength at high temperatures so that it does not rupture under the pressures generated during thermal runaway. Local hot spots should not reduce the mechanical strength of the battery casing, which may cause a weak point for the premature rupture of the battery.
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