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Understanding the Non-Collision Related Battery Safety Risks in Electric Vehicles a Case Study in Electric Vehicle Recalls and the LG Chem Battery

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ABSTRACT Electric vehicles (EV) are considered the future of the automobile industry due to their high energy conversion efficiency and environmental friendliness. However, there are safety risks associated with Li-ion batteries, including the potential for fires and explosions. This paper reviews the challenges facing the electric vehicle market regarding the implementation of Li-ion batteries. It then presents two case studies of electric vehicles that experienced safety-related recalls which were not associated with vehicle collisions. For comparison, a history of Li-ion battery safety issues from the same brand in other applications than EV and the company's reactions are provided. The case study and review of issues in other applications show a lack of consideration for customer safety, amplified by the additional risk used in an EV. The paper then explores corrective actions performed and analyzes how the actions will not address the root cause; additionally, contributing to a performance reduction. Recommended corrective actions for future implementation of EV batteries are provided.

INDEX TERMS Electric vehicles, Li-ion batteries, exothermic event, reliability and risk, safety.

I. INTRODUCTION TO EVs AND EV BATTERIES

In the electric vehicle (EV) industry, Li-ion batteries are the dominant power source. Li-ion battery adaptation is due to environmental concerns, high power density, and improved performance. Factors influencing Li-ion batteries' use include performance capabilities (e.g., charge time and range per charge), reliability and safety, the latter requiring special attention due to the batteries' volatile nature and high energy, resulting in fires or explosions.

With the expansion of the EV market, recalls are increasing. An early example of a large-scale recall occurred in 2012 with A123 Systems Li-ion batteries. Potential performance issues were the first stated reason for the recall. The root cause found by A123 was a miscalibration of a welding machine used to assemble Li-ion pouch cells [1]. Safety-related recalls reporting fire are not only caused by collisions but are documented in non-collision events as well [2]. Battery quality issues can result in non-collision-related fires. Cases of batteries catching fire, and in some instances exploding, have been reported since the inception of EVs. For example, Tesla is under investigation by the National Highway Traffic Safety Administration (NHTSA) regarding fire incidents in Tesla Model S and Model X EVs [3]. However, a study done by O'Mallery *et al.* found that during collisions, the risk of fire or explosion is not greater in EVs than in other automobiles [4].

Fires have also occurred in EVs that were not involved in a collision. For example, in early 2018, a Tesla Model X caught on fire twice within 24 hours, both times while parked [5]. A Tesla Model S was reported catching fire while parked. Catching fire while parked has been reported twice, occurring in Shanghai and San Francisco [6]. These fires' root cause was linked to road debris hitting the vehicle's underbody, puncturing the battery [7], and manufacturing errors [8]. Non-collision-related fires are reported involving several EV makers; NIO ES8 in China, Hyundai Kona, Chevrolet Bolt, Ford Kuga/Escape, and Chrysler Pacifica Hybrids. These reports have all occurred in 2020, highlighting the rise in quality control issues leading to fire-risks within the EV industry.

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The quality control is with the EV maker and quality control of manufacturing practices with the Li-ion battery suppliers.

The largest Li-ion battery manufactures are linked to the recalls as commonly as the EV maker. Samsung SDI supplies the Kuga battery pack. The Ford Kuga plug-in hybrid EV has been recalled in Europe due to contamination in the manufacturing process of their battery packs [9]. BMW also sources batteries from Samsung SDI. Battery manufacturer CATL is another battery supplier to BMW for a portion of their fleet and is also involved in recalling the issue [10]. The Renault electric vehicle Zoe manufactured between September 23, 2019, to December 18, 2019, is under recall because "A production defect in the battery may lead to a short circuit. The production defect may cause overheating and damage to the electrical systems, increasing the risk of fire" [1][2]. Audi has issued a voluntary recall on the E-Tron because of a risk for battery fires. In this case, the wiring harness defect can lead to moisture ingress to the LG Chem supplied Li-ion cell. The resultant moisture within the Li-ion cell may lead to a thermal runaway and fire [11]. The partnership of Hyundai Motor and LG Chem is deteriorating because of the fires [3].

This paper presents two case studies involving fires in LG Chem Li-ion cells used in the Hyundai Kona and the Chevrolet Bolt. There is a review of Li-ion cell-induced risks facing the EV market. Section 2 presents the case studies concerning LG Chem in the EV industry. For comparison, the following section examines how LG Chem Li-ion batteries perform in other industries. In section 4, details of the corrective action are presented and analysis is given to explain the negative effect of the attempted corrective action. Section 5 provides recommended actions to address the underlying issues. The paper concludes in section 6 with findings.

II. CASE STUDY OF LG CHEM LI-ION BATTERY ISSUES IN EVs

LG Chem is one of the primary EV battery suppliers and their batteries power EVs around the world. In Europe, LG Chem is the vendor for Volkswagen, BMW [4], and Renault. In Asia, LG Chem provides batteries for Hyundai [3] and Tesla cars manufactured in China. General Motors [5] and Volvo [6] use LG Chem batteries in the North American market. LG Chem is producing Li-ion batteries at a high rate. The LG Chem factory in Ohio is expected to output 30 GWh, and the total world output from LG Chem is 100 GWh [12].

GM's 2017 Chevy Bolt EV has a 60 kWh, 350 V Li-ion battery pack supplied by LG Chem. The battery pack includes five sections that are further divided into ten modules. The battery pack comprises 288 Li-ion cells arranged into 96 groups with three cells in parallel per group (3p96s) [13]. The battery pack is expected to support 200 miles of range. Each cell has a nominal voltage of 3.6 V and a nominal capacity of 60 Ah. The cathode's major chemistry is lithium nickel oxide, lithium cobalt oxide, and lithium magnesium oxide chemistry. A 2019 Hyundai Kona battery pack has nominal energy of 64 kWh and a nominal voltage of 356 V. The battery is designed for 258 miles on one full charge. The Hyundai design has five modules made of 294 cells. Like the Chevy Volt design, the pack configuration is 3p98s.

LG Chem has been at the center of significant recalls involving the Chevy Bolt [14] and Hyundai Kona [15]. GM has two types of EV recalls in the past, one for the Chevrolet Volt with Model 2013. This recall was issued in June 2018. In the recall report, the reason is stated as the issues with battery balancing can cause low-voltage conditions, and the vehicle can even lose propulsion power completely. The other type is the Chevrolet Bolt EV with models from 2017 to 2019. The second recall was issued in November 2020 due to reports of the Li-ion battery catching fire. Hyundai initiated a recall when a report of a fire in 2019-2020 Hyundai Kona occurred.

A. GENERAL MOTORS

A recall of the 2013 Chevy Volt, a hybrid EV, issued in June 2018 was the first recall issued for GM EVs. The recall was not fire-related but deemed a product safety issue. The recall stated that a software update might have introduced an error that prevented the BMS from balancing the voltage among the individual battery cells [16]. The recall indicates that a software update will correct the cell balancing fault but does not provide details about the software error or if the thermal management system is active or passive.

As cell performance varies from one to another in a battery pack, cell voltage and state of charge (SOC) imbalances occur in the battery pack where cells are connected in series. Each cell's current remains the same in a series connection, but each cell's voltage and SOC differ. Safety and reliability concerns limit individual cells' operation voltage range between the charge cut-off voltage and the discharge cut-off voltage. Once one individual cell in a series connection reaches the discharge cut-off voltage, the entire series connection will stop discharging. Thus, many cells are never fully charged or discharged. The available capacity of the battery pack is subject to the minimum capacity of the individual cells.

To prevent the Li-ion cells' imbalances from affecting the battery pack's safety and reliability, battery management, specifically cell balancing, is required. There are two types of cell balancing, active and passive. Passive balancing employs a balancing device to control the balancing current through each cell by dissipating cells' excess energy with higher SOC. This method increases the available capacity of a series connection up to the minimum capacity of individual cells. Active balancing moves the extra charge from cells with higher SOC to cells with lower SOC. The active balancing method can increase the available capacity and energy more than passive balancing.

In November of 2020, GM and the NHTSA determined through an investigation into non-crash-related fires that the Chevy Bolt posed a safety risk in select 2017-2019 model year. All of the vehicles produced in 2017-2018 and a select number of EVs manufactured in 2019 were built with high-voltage batteries produced at LG Chem's Ochang, Korea facility. The Li-ion cells produced at this facility may pose a fire risk when charged to full or very close to full capacity. The recall involves nearly 69,000 Chevrolet Bolt EVs worldwide that pose a fire risk after five reported fires and two minor injuries [14]. In October 2020, NHTSA opened a probe after reviewing three Bolt EVs catching fire under the rear seat while parked. The probe covers 77,842 Chevy Bolt EVs from the 2017 through 2020 model years [17]. It is unknown if the ongoing investigation is related to the exact underlying failure mechanism as the recall.

B. HYUNDAI

From 2019 to 2020, over sixteen Hyundai Kona EVs caught fire. The fires occurred in Korea, Canada, and Europe. In a filing to the US National Highway Traffic Safety Administration (NHTSA) in October 2020, Hyundai blamed ''internal damage to certain cells of the Li-ion battery increasing the risk of an electrical short circuit.'' The battery maker, LG Chem, denied any cell defects, saying a joint investigation was underway. It is worth noting, in China, Hyundai does not use the LG Chem battery but rather CATL batteries. The recall above does not apply to Hyundai's sold in China. Hyundai is continuing to actively investigate this condition for the identification of the root cause.

Hyundai is recommending an update to the EV software as a mitigation to the recall. The recall is issued for more than 74,000 EVs in South Korea, the United States, Europe, and Canada to update the battery management system (BMS). As of March 2021, approximately 23,000 Kona EVs in South Korea have completed the software upgrade. During the upgrade, 800 EVs were found to have battery defects requiring replacement of affected modules, according to the office of lawmaker Jang Kyung-tae, which was briefed by South Korea's transport ministry.

III. NON-EV RELATED ISSUES WITH LG CHEM BATTERIES

In addition to EVs, numerous safety issues caused by LG Chem Li-ion batteries have been reported in other applications. For example, a battery energy storage system (BESS) using LG Chem Li-ion batteries caught fire in Arizona in 2019 [18]. The LG Chem ''RESU 10H'' Li-ion residential energy storage system was put on recall in 2020 by the US Consumer Product Safety Commission (CPSC) after causing several fire incidents. Based on the CPSC's recall announcement, ''the home batteries can overheat, posing a risk of fire and emission of harmful smoke'' [19]. An investigation by project owner Arizona Public Service concluded that cell failure kicked off the chain of events that led to the explosion. Insufficient fire suppression and lack of ventilation for explosive gases in the battery enclosure exacerbated the incident. There were also reports of severe injuries caused by LG Chem Li-ion cells used in electronic cigarettes with fire or explosion [20]. LG Chem has faced multiple lawsuits related to electronic cigarette battery incidents [21] [22]. According to LG Chem, the cathode material composition is Li[NixCoyMnz]O2 (NCM111, NCM424, NCM523, NCM622, NCM712) [23]. Although letting Ni content take more percentage than the Mn content raises the capacity, the safety is lowered [24].

Customers are expecting LG Chem to improve the safety of Li-ion cells. However, on February 3, 2020, LG Chem released an advertisement in the Washington Post advising the public not to use (handle) Li-ion batteries, ''Don't Buy It. Don't Sell It. Stay Safe'' [25]. LG Chem stated that ''LG Chem will not sell 18650 or 21700 Li-ion battery cells to consumers''. By running ads instead of ensuring the safety of its batteries when they inevitably end up in the hands of consumers, LG Chem is avoiding its social and corporate responsibility. LG Chem should devise safe batteries by employing effective internal safety mechanisms, such as a positive temperature coefficient resistor (PTC), current interruption device (CID), and shutdown separators, preventing thermal runaway battery fires and explosions.

IV. RECALL ACTIONS AND THE LONG-TERM EFFECTS

Hyundai and General Motors' initial corrective action is to update their BMS software and regulate the battery's operating range. Hyundai found during software updates that enough Li-ion cells were damaged to require further action. Hyundai proceeded with Li-ion batteries' modular replacements, indicating that a software-only solution was inadequate to reduce risk. This information highlights the EV industry's difficulty distinguishing the faults of BMS (EV makers) or battery cells (battery manufacturers) in the safety incidents.

There are limitations to the BMS's capability of correcting failures. For example, GM determined the root cause of the Chevy Bolt fire incidents to be a short circuit. The GM recall states that the short circuit may occur when at ''full or very close to full capacity.'' The Hyundai recall states that the short circuit results from internal damage to specific cells. There are many potential reasons for an internal short circuit occurring, such as design/manufacturing defects.

The internal short circuit is a fault that occurs fast at the cell level. Nevertheless, the BMS is not to blame for the two case studies because a BMS can barely detect or handle the internal short circuit failures. Both recalls state the short circuit as the cause. The internal short circuits are an issue of LG Chem's manufacturing practices based on the available information. It is worth noting that Hyundai sourcing more cells from other suppliers to avoid being solely reliant on LG Chem [26].

Hyundai and LG Chem are at odds over the fires' root cause as South Korea's safety agency investigates the case. LG denies the battery cells are defective [15]. LG Chem said the cause of the fires had not been determined. A reenactment experiment conducted jointly with Hyundai had not led to a fire, so the fires could not be attributed to faulty battery cells [26].

While GM investigates the fire's root cause, GM advised Bolt EV owners to change their vehicles' charge settings, limiting charges to 90% to reduce fire risk. However, this software update may not remove the fire risks. The reasons are as follows.

The capacity value represents the amount of time that a fully charged (100% SOC) battery can operate. When specified capacity value refers to the battery's deliverable capacity, it is not a theoretical value. When a battery company manufactures a battery, it checks (measures) this capacity value to ensure that the value given on the battery will be met (e.g., can be "delivered"). It is not a value for a battery charged or discharged to an unsafe value. There should be no problem charging a battery to 100% SOC, which corresponds to the specified high cut-off voltage. GM and Hyundai did not report whether the battery SOCs were above 90% when these fire issues occurred. The fire issues more likely stem from the battery cells.

An example of insufficient or wrong corrective action was given on May 1, 2021. A Chevy Bolt, which had already had the temporary corrective action applied, still had a fire while parked in a garage. The Chevy Bolt was not charged to 100%, and the owner had intentionally stopped the charge when it reached a range of 160 miles, or approximately 75% [27]. Additionally, on April 29, 2021, GM announced that the initial recall may not be sufficient and that some battery modules may also need to be replaced. A noticeable comment in the recall update states that the 90% limitation will be removed once diagnostic software is applied to the EV [28].

In addition to not addressing the root cause of the failures occurring in the field, the mitigation plan to change the BMS software has other adverse effects. The software update limits the upper SOC level to 90%, resulting in reduced available battery capacity by 10%. For a battery that discharges from 100% SOC (full charge) to 0% SOC (full discharge), the available battery energy E_b is:

$$E_b = \int_{t_{0,\mathrm{SOC}=100\%}}^{t_{end,SOC=0\%}} V_b I_b \, dt \tag{1}$$

where E_b is the discharge energy of the battery, t, V_b is the battery terminal voltage, I_b is the battery discharge current. The integral in equation 1 ranges from the start of discharge (t_0) to when the battery voltage reaches the discharge cut-off voltage (t_{end}).

After the software update, the available battery energy $E_{b,new}$ is:

$$E_{b,new} = \int_{t_{0,\mathrm{SOC}=90\%}}^{t_{end,SOC=0\%}} V_b I_b \, dt \tag{2}$$

For ease of calculation, the battery discharge current I_b is assumed to be constant, then:

$$E_b = I_b \int_{t_{0,\mathrm{SOC}=100\%}}^{t_{end,SOC=0\%}} V_b \, dt \tag{3}$$

$$E_{b,new} = I_b \int_{t_{0,\mathrm{SOC}=100\%}}^{t_{end,SOC=0\%}} V_b \, dt \tag{4}$$

Assuming that the battery delivers all of its rated capacity during discharge from 100% SOC to 0% SOC. The battery capacity C_b is calculated as the integral of the battery current over the discharge process:

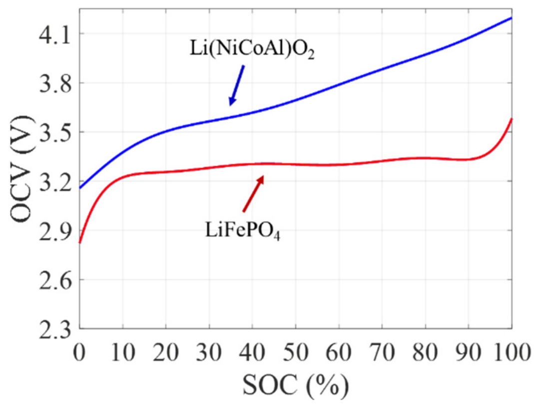

FIGURE 1. Open-circuit voltage (OCV) vs. SOC.

$$C_{b\_rated} = \int_{t_{0,\mathrm{SOC}=100\%}}^{t_{end,SOC=0\%}} I_b \, dt \tag{5}$$

The battery discharge time to 0% SOC before and after the software are:

$$\Delta t = t_{end,SOC=0\%} - t_{0,\mathrm{SOC}=100\%} = \frac{C_{b\_rated}}{I_b} \tag{6}$$

$$\Delta t_{new} = t_{end,SOC=0\%} - t_{0,\mathrm{SOC}=90\%} = \frac{90\% * C_{b\_rated}}{I_b} \tag{7}$$

The ratio of the available energy after the software update to the available energy before software update is:

$$\begin{aligned} \mathrm{R} &= \frac{E_{b,new}}{E_b} = \frac{\int_{t_{0,\mathrm{soc}=90\%}}^{t_{end,SOC=0\%}} V_b dt}{\int_{t_{0,\mathrm{SOC}=100\%}}^{t_{end,SOC=0\%}} V_b \, dt} \\ &= \frac{\int_{t_{0,\mathrm{soc}=90\%}}^{t_{end,SOC=0\%}} V_b \, dt}{\int_{t_{0,\mathrm{SOC}=100\%}}^{t_{end,SOC=90\%}} V_b dt + \int_{t_{0,\mathrm{SOC}=90\%}}^{t_{end,SOC=0\%}} V_b \, dt} \end{aligned} \tag{8}$$

If the battery voltage, V_b, is constant, then the available energy after the software update is 90% of that before the software update:

$$\mathrm{R} = \frac{E_{b,new}}{E_b} = \frac{\int_{t_{0,\mathrm{soc}=90\%}}^{t_{end,SOC=0\%}} V_b dt}{\int_{t_{0,\mathrm{SOC}=100\%}}^{t_{end,SOC=0\%}} V_b \, dt} = \frac{\Delta t_{new}}{\Delta t} = 0.9 \tag{9}$$

A battery's voltage decreases with SOC, shown in Figure 1. V_b is higher at 90%-100% SOC than it is at 90%-0% SOC.

The state of charge's nonlinearity indicates that reducing the capacity to 90% is not equivalent to the expected 10% reduction.

$$\int_{t_{0,\mathrm{SOC}=100\%}}^{t_{end,SOC=90\%}} V_b dt > \frac{1}{9} \int_{t_{0,\mathrm{SOC}=90\%}}^{t_{end,SOC=0\%}} V_b \, dt \tag{10}$$

Therefore, the available energy after the software update is less than 90% of the available energy before the software update. The mileage will be reduced by more than 10%, making customers charge the EVs more frequently and increase the range anxiety. Additionally, the BMS software update does not address the Li-ion cell's hardware defects, causing the non-collision-induced fires. EV makers must take action to mitigate the risks identified in the recalls. However, without the support of the Li-ion manufacturers, the customers will suffer through ineffective mitigations.

V. RECOMMENDED ACTIONS

The case studies show that the issues related to the EVs are not fundamentally related to software issues. Software is not causing over or undercharging and software has not been found to put the battery into an abusive state. The software is not changing the operating environment to lead to increased risk to the battery. The underlying failure mechanisms that can lead to a fire or explosion of a Li-ion battery are hardware problems of battery cells. Using the software, at best, will mask the issue and could reduce the risk to customer safety by alerting of imminent hardware failures. However, this does not remove the risk by addressing the root cause. The cause is occurring in manufacturing, either at the battery level or during the assembly of the EV.

Addressing the issue begins with an acknowledgment of a need for emphasis on customer safety. Putting customer safety first instills a process that follows quality practices wherein corners are not cut for speed or revenue. The practice of putting customer safety first must take place at both the EV maker and the Li-ion manufacturers. The quality system of the EV maker should extend to their supply chain and be inclusive of how they accept Li-ion batteries.

As discussed in section 3, LG Chem has a record of not putting customer safety first. The size and number of batteries used in EVs increase the risk of harm. Li-ion battery vendors should follow manufacturing best practices such as performing process failure modes effects analysis (PFMEA), out-of-box testing, contaminate free workspace, data-driven continuous improvements, and simplifying human interactions. The use of automation equipment is prevalent but must be maintained to reduce the introduction of systemic defects.

EV makers should implement supply chain reliability practices. These practices include quality audits, ongoing reliability testing, incoming quality acceptance screening, and monitoring statistical process control metrics from their Li-ion battery vendors. In addition to the supply chain activities, EV makers must also perform reliability practices at the EV level to assure safe operation once the Li-ion battery is integrated into the rest of the system.

VI. CONCLUSION

There is an increasing number of incidents with EV's due to failures of Li-ion batteries. Li-ion batteries introduce safety risks to customers that are not experienced in other automobiles. The novel safety-related issue addressed in this paper results in a fire or explosion when the EV has not experienced a collision. Two cases involving LG Chem Li-ion batteries show a gap in awareness regarding non-collision risks. In both cases, the EV makers, GM and Hyundai, have issued a recall for thousands of automobiles without a root cause. In the case of Hyundai, the recall presented is a catalyst for finding a new Li-ion manufacturer.

The EV industry lacks safety guidance regarding battery vendor selection. As one of the significant EV battery suppliers, LG Chem has a history of recalls in EVs but is reluctant to admit ownership of their faults. The information provided in the recall reports and the analysis of these events shows a debate between EV makers and battery manufacturers on fault ownership. A study of the reported issues shows that EV makers tend to rely on software upgrades as mitigation. A software corrective action will, at best, reduce the likelihood of experiencing the failure; however, it will not eliminate the safety risks. Also, the software modifications have other adverse effects on the performance of the EV.[1]

To address the problems presented in this paper, Li-ion battery manufacturers and EV makers must determine the root cause for incidents where a fire resulted without a collision occurring. The underlying failure mechanism leading to a fire or explosion is addressable by the Li-ion battery manufacturers. However, the Li-ion battery manufacturers must acknowledge the risk of quality control problems and focus on corrective actions, opposed to focusing on deflecting blame. The EV makers should focus on corrective actions addressing the root cause, not on mitigation paths that may not sufficiently reduce the risk.

The Li-ion battery manufacturer selection process requires analysis of the organization's reliability capabilities and assessing their quality control procedures by the EV maker. Li-ion battery manufactures have a history of sacrificing quality for speed to market, often at the detriment of the public. The behavior of not acknowledging their responsibility for safety to the customer is not unique to the EV industry. LG Chem has safety-related Li-ion battery failures in other markets. For the betterment of public safety, Li-ion battery manufacturers should be held accountable like the EV makers.

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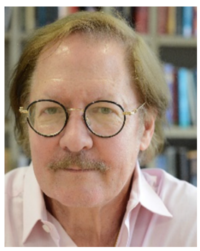

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