Electric Vehicle Battery Safety Challenges

Alec Krabbe, Standards Project Engineer
Data Science & Engineering Team | Aug 2023

Background

Many countries worldwide have announced pledges to achieve net-zero emissions by 2050 or sooner.[1] Net zero aims to balance the amount of greenhouse gases emitted with the amount removed from the atmosphere. One key sector that is moving toward decarbonization to reach this emissions goal is transportation, which accounts for about a quarter of global energy-related CO_2 emissions.

Electric vehicles are a promising solution in helping to reduce emissions from transportation, as they run on renewable energy instead of fossil fuels. EVs also have lower operating and maintenance costs and provide environmental benefits such as improved air quality and energy security. However, widespread EV adoption faces challenges, such as high upfront costs, lack of charging infrastructure, consumer awareness and preferences, and battery safety issues.

Summary

Battery safety is paramount as EV batteries store substantial energy and can pose fire and explosion risks if not properly designed, manufactured, used, and disposed of. Battery Safety for EVs can be improved using advanced materials, testing methods, monitoring systems, and recycling processes. Moreover, battery safety standards and regulations must be harmonized and adopted across countries and regions to help ensure consistent and elevated levels of protection for the EV supply chain, users, and the environment.

Harmful occurrences and hazards related to EV batteries must be understood and addressed in pursuit of the net-zero pledges aimed at the transportation sector's decarbonization. These include:

- Thermal runaway: This is a condition in which the battery cell generates more heat than it can dissipate, rapidly increasing temperature and pressure. Thermal runaway can cause violent cell venting, fire, smoke, and explosion.
- Off-gassing: This is the release of gases from a lithium-ion battery that can occur when the battery is damaged, overheated, overcharged, or otherwise stressed. Off-gassing can lead to thermal runaway.
- Stranded energy: This is the electrical energy that remains in a high-voltage lithium-ion battery after it has been damaged or exposed to extreme conditions, such as a crash or a fire. Stranded energy poses a severe risk to emergency responders and crash scene workers, as it can cause electric shock, thermal runaway leading to fire or explosion, and battery reignition.
- Electric shock: This is a severe and potentially fatal hazard when handling or working with EVs. EVs use high-voltage lithium-ion batteries that store large amounts of energy and can deliver a powerful electric shock.
- Fire: EV battery fires are difficult to extinguish and can reignite even after being put out. Lithium-ion batteries inside electric vehicles produce oxygen when they burn, which continues to feed flames and makes it harder to extinguish the fire.
- Explosion: EV battery explosions can cause severe injuries and property damage.
- Chemical Exposure: When an EV battery suffers abuse or ruptures, it can release various chemicals that may harm humans and the environment.

These safety challenges can be mitigated by designing and testing the battery materials, components, and systems according to relevant standards and regulations. Additionally, off-gas detection systems should be implemented to monitor the battery condition and alert the users of any signs of off-gassing. Finally, emergency responders and crash scene workers should be trained to safely handle and dispose of damaged electric vehicles with stranded energy in their batteries.

EV Battery Hazards and Harmful Occurrences

EVs use high-density batteries to store and deliver energy for propulsion. These batteries can pose various risks to operators and owners of EVs. This section provides an overview of EV battery hazards and associated harmful occurrences to which operators and owners can be exposed.

Hazards

A **hazard** is a situation or condition that poses a potential risk of harm to people, property, or the environment. Hazards can vary in severity, frequency, and predictability and require different prevention, mitigation, and response strategies. The following addresses the hazards of thermal runaway, off gassing, and stranded energy,

Thermal Runaway

Thermal runaway is a severe hazard associated with lithium-ion EV batteries that can cause violent cell venting, fire, smoke, and explosion.[2]

One of the leading causes of thermal runaway is an internal short circuit, which can occur due to mechanical damage or defects in the cell separator. Other causes include overcharge, over-discharge, external short circuits, and exposure to extreme temperatures.

Mitigation:

Designing and testing the battery materials, components, and systems according to relevant standards and regulations is essential. UL Research Institutes is a leading organization that provides research and testing services for electrochemical safety. The findings of UL Research Institutes have been used to develop a testing methodology to evaluate the material performance of battery enclosures under thermal runaway conditions. This methodology can help resin manufacturers and material suppliers optimize their products for EV applications.

Additionally, venting is a process that allows gases to flow in and out of the battery enclosure to help prevent problems caused by temperature and pressure changes. Venting can also help avoid thermal runaway conditions by allowing gases to escape. However, if the venting capability of the battery is exceeded, additional pressure relief is needed to avoid rupturing the pack enclosure.[3]

Off Gassing

Off-gassing is the release of gases from a lithium-ion battery that can occur when the battery is damaged, overheated, overcharged, or otherwise stressed. Off-gassing is one of the significant hazards of EV batteries, as it can lead to thermal runaway and pose risks to human health, safety, and the environment.[4]

Off-gassing can produce toxic and flammable gases like carbon monoxide, hydrogen, methane, and other hydrocarbons. These gases can cause respiratory irritation, nausea, headache, and even death if inhaled in high concentrations. They can also ignite if they reach their lower explosive limit and encounter a spark or flame, potentially resulting in an explosion that can damage the vehicle and its surroundings.

Several factors, such as physical damage, elevated temperature, excessive discharge, or failure of the battery management system, can trigger off-gassing. Off-gassing usually occurs during the initial stages of battery failure before smoke or fire are visible. Therefore, detecting off-gassing immediately and taking preventive measures to avoid thermal runaway is vital. Some measures include isolating the faulty battery, disconnecting the power source, cooling the battery, and ventilating the area.

Mitigation:

EV batteries should be designed, installed, operated, and maintained with care and caution. Off-gas detection systems should be implemented to monitor the battery condition and alert the users of any signs of off-gassing. Off-gas detection can help protect people and property from harm by alerting users of thermal runaway before it begins.

Stranded Energy

Stranded energy is a term that refers to the electrical energy that remains in a high-voltage lithium-ion battery after it has been damaged or exposed to extreme conditions such as a crash or a fire. Stranded energy poses a severe risk to emergency responders and crash scene workers, as it can cause electric shock, thermal runaway leading to fire or explosion, and battery reignition, which can take place at an extended period postinitial event. Therefore, it is crucial to have proper procedures and guidelines for safely handling and disposing of electric vehicles with stranded energy in their batteries.

Mitigation:

Some of the recommended practices include using personal protective equipment, isolating the battery from the vehicle's electrical system, monitoring the battery temperature and voltage, applying water or foam to cool down the battery, transporting and storing the battery in a safe and ventilated location, and contacting the vehicle manufacturer for further assistance. Stranded energy is a significant challenge for the electric vehicle industry, as it affects lithium-ion batteries' safety, performance, and sustainability.[4]

More research is needed on mitigating or de-energizing stranded energy in damaged batteries to help reduce the hazards associated with thermal runaway and battery fires.

Harmful Occurrences

A **harmful occurrence** is an event or situation that causes damage, injury, or loss to a person, property, or environment. Harmful occurrences can have short-term or long-term effects on the well-being of individuals and communities. The following addresses the harmful electric shock, fire, explosion, and chemical exposure occurrences.

Electric Shock

Electric shock is a severe and potentially fatal hazard when handling or working with EVs. EVs use high-voltage lithium-ion batteries that store large amounts of energy and can deliver a powerful electric current. The voltage in EV batteries is direct current (DC) as opposed to alternating current (AC). An EV's DC voltage is much higher than the 12-volt batteries used for gasoline engines and potentially more dangerous than AC, with nominal battery pack voltages typically between 400-800 volts and higher – compared to the household standard of 110 volts for AC.[5]

Electric shock can happen in various EV battery scenarios, such as during regular operation, after a crash, during a fire, or maintenance or repair. Some factors that increase the risk of electric shock are damage to the battery or its components, exposure to conductive liquids, loss of insulation or isolation, and thermal runaway.

Mitigation:

Following vehicle manufacturers' and emergency responders' safety guidelines and procedures is essential to help prevent electric shock from EV batteries. Some general precautions include wearing protective equipment, avoiding contact with high-voltage parts, disconnecting the battery if possible, using non-conductive tools and materials, and keeping a safe distance from the vehicle in case of fire or smoke.

Fire

Lithium-ion batteries can catch fire if damaged, defective, or overheated, causing thermal runaway. These fires are difficult to extinguish and can reignite even after being put out. When a lithium-ion battery overheats, it gives off oxygen gas, which can turn a spark into a blaze, making it more difficult to extinguish. Even though gasoline is much more energy-dense than a lithium-ion battery, the battery produces oxygen when it burns.[6,7] The burning battery still has stored energy and can create fuel, making it far more challenging to extinguish than a gasoline fire.[8]

Mitigation:

Fire services have two main options for tackling fires in EVs: let the fire burn out or extinguish it.[9] Firefighting foam and fire blankets can smother the fire, and pancake nozzles can apply a cooling spray to the battery box by sliding underneath the vehicle. Piercing nozzles aim to puncture the battery box and deliver water directly to the cells.

Note: While class D fire extinguishers combat combustible metal fires, lithium-ion batteries do not contain solid lithium metal, making the extinguisher ineffective.

The U.S. Fire Administration has published standardized guides for electric vehicles and lithium-ion battery response that are now available for easy access to critical information for first responders.[10]

Explosion

An EV battery explosion can cause severe injuries to vehicle occupants and the surrounding environment. When a lithium-ion EV battery undergoes thermal runaway, it can generate intense heat and release flammable gases that can ignite and cause an explosion. Some possible injuries include scars, hearing and vision impairment, permanent disability, and death. In addition, an EV battery explosion can also damage the vehicle itself and other nearby structures or vehicles.

Mitigation:

Ensure that the EV purchased is utilizing quality and safety-tested batteries. Follow manufacturer procedures for proper battery charging, handling, and disposal.

Chemical Exposure

When an EV battery suffers abuse or ruptures, it can release various chemicals that may harm humans and the environment. One of the main components of an EV battery is the electrolyte, usually a flammable liquid containing lithium salts, such as lithium hexafluorophosphate ($LiPF_6$) or other fluorine-containing compounds. If the battery overheats, the electrolyte can evaporate and vent out from the cells, forming a gas that may ignite or explode. The gas can also contain toxic fluoride compounds, such as hydrogen fluoride (HF) and phosphoryl fluoride (POF_3), which can cause severe irritation and damage to the eyes, skin, lungs, and other organs. According to a study by Larsson et al., the amount of HF emitted from a lithium-ion battery fire can range from 20 to 200 mg/Wh of nominal battery energy capacity.[11] Another study by the Institute for Energy Research estimated that the lithium extraction process for EV batteries uses about 500,000 gallons of water per metric ton of lithium, which can negatively impact local water resources and ecosystems.[12]

Chemical runoff from firefighter response to an EV fire is also a significant concern due to the amount of water needed to resolve the incident effectively. The water used to extinguish the fire can wash battery chemicals into the ground and contaminate nearby water sources, leading to serious health problems for people, animals, and plants that rely on those water sources. Additionally, the chemicals can harm aquatic life and disrupt the ecosystem.

Mitigation:

Handle EV batteries carefully and dispose of them properly to prevent potential leaks and fires that could harm people and the planet.

Firewater runoff can be mitigated by using foam or dry chemical extinguishers instead of water to put out electric vehicle fires, applying absorbent materials or barriers to contain and collect firewater runoff at the scene of the fire, or transporting and disposing of firewater runoff and contaminated materials following local regulations and guidelines.

Causes of EV Battery Hazards

Safety risks of lithium-ion EV batteries, such as fire and explosion, can be caused by several factors, including physical damage, manufacturing defects, improper installation or repair, overcharging or overheating, and defects in the Battery Management System (BMS).

Physical Damage

If an EV battery or battery compartment is damaged, it can explode, catch fire, and emit hazardous gases. The potential for physical damage is present during events such as a motor vehicle accident, exposure to abnormal external conditions, and intentional or unintentional abuse.

Manufacturing Defects

Manufacturing defects such as improper design and construction can cause battery hazards. The lithium-ion cell and battery manufacturing process requires stringent quality control. Failures can remain latent until triggered during product use.[13] For example, flaws in production can cause metallic particles (impurities) to seep into the lithium-ion cell during manufacturing. Another defect could be the thinning of separators, which could prove detrimental in actual use.

Improper Installation or Repair

Improper installation or repair of EV batteries can cause hazards such as leaks or overheating, leading to significant injury. For example, mishandling the high-voltage battery and associated components during installation or repair can present potential high-voltage shock hazards. Technicians should always follow the safety guidelines and procedures provided by vehicle manufacturers and emergency responders when handling EV batteries.[14]

Overcharging or Overheating

Overcharging and overheating are some of the reasons for EV battery cell damage. Overcharging can occur when a battery charges too rapidly or externally short-circuit. Overheating can be caused by prolonged exposure to defective voltage regulators and converters or the improper use of chargers.[4]

Defective voltage regulators: Voltage regulators are responsible for keeping the voltage output of an alternator within a safe range. If a voltage regulator is defective, it may allow the voltage to rise to dangerous levels, which can lead to overheating.

Defective DC-to-DC converter: The converter is a small but powerful device that converts the high-voltage electricity from the battery to the 12-volt electricity used to power the car's electrical systems. The converter generates heat as it converts the electricity, and if it is not adequately cooled, it can overheat.

Improper use of chargers: Chargers can also cause overheating if misused. For example, using a charger not designed for a specific device can lead to overheating.

Defects in the Battery Management System

Some common BMS failures include unstable power supply, wiring harness issues, sensor errors, and software bugs. These issues can lead to incorrect readings, loss of communication, and delays in detecting or responding to potential defects.

Hazard Mitigation Systems

Effective EV battery hazard mitigations rely on adequately functioning venting and battery management systems. Venting systems prevent the buildup of gases within the battery pack, which can lead to thermal runaway and potential fires. Meanwhile, battery management systems monitor and control the battery's temperature, voltage, and current to ensure safe and optimal performance. Together, these systems help to minimize the risk of EV accidents and promote safer driving experiences.

Venting

Venting is a critical safety feature for EVs and batteries. It allows the escape of gases that build up inside the battery pack, such as hydrogen and oxygen. These gases can be generated during regular operation or a battery failure.

There are two main types of venting systems used in EVs:

Passive venting, also called stage one venting, relies on an expanded polytetrafluoroethylene (ePTFE) vent to allow pressure equalization while preventing contaminants from entering the enclosure. ePTFE membranes appear opaque to the naked eye and offer ingress protection against water, dust, solvents, and other contaminants.[15]

Active venting, also called stage two venting, is designed to handle situations with rapid pressure buildup in a thermal runaway event. The vent opens fully to allow rapidly expanding gases a controlled escape, preventing further damage to remaining cells and an uncontrolled enclosure explosion.[15]

It is important to note that venting systems are not a definitive solution and may not prevent all fire or explosion incidents.

Battery Management System

A BMS is an electronic system that monitors and controls a battery or battery pack. It is an essential part of an EV as it ensures the safe and efficient operation of the battery.

A BMS typically consists of the following components:

A battery sensor: This sensor monitors battery voltage, current, and temperature.

A battery controller: This controller uses sensor data to control the battery's charging and discharging.

A battery protection circuit: This circuit protects the battery from overcharging, over-discharging, and short-circuiting.

A battery communication interface: This interface allows the BMS to communicate with other components of the EV, such as the motor controller and the battery charger.

The BMS uses the data from the sensor to monitor the battery's state of charge (SOC) and state of health (SOH). The SOC is a measure of how much charge is remaining in the battery, while the SOH is a measure of the battery's overall health. The BMS uses this information to control the charging and discharging of the battery and ensure that it operates within its safe operating limits.

The BMS also uses sensor data to detect battery problems, such as overcharging, over-discharging, or short circuits. If the BMS detects a problem, it takes steps to protect the battery, such as shutting down the charging or discharging process. By monitoring the battery's state of charge and state of health, the BMS can help to extend the battery's life and prevent problems. The benefits of a BMS in an EV are increased battery safety, improved battery performance, increased battery efficiency, and reduced costs associated with maintenance or replacement.

The BMS is a complex system that requires a variety of sensors to function correctly. These sensors typically monitor voltage, current, temperature, pressure, humidity, and gas. The BMS uses the data from these sensors to monitor the battery's SOC, SOH, and overall performance. The BMS can then protect the battery and improve its performance.

Test Methods in UL Safety Standards

UL safety standards for batteries go beyond safety testing by specifying that batteries meet specific design, component, BMS, labeling, and documentation requirements. This comprehensive approach helps to promote the safety of EV batteries.

EV batteries are subjected to various tests to comply with UL standards. These tests are designed to help ensure the safety of the batteries and prevent them from catching fire or exploding.

The tests that EV battery systems are subjected to include the following:

Electrical Tests:

Short-Circuit: Conducted on fully charged samples to determine their ability to withstand an external short circuit.

Overcharge: Intended to evaluate an electrical energy storage assembly (EESA) and the ability of its associated protection circuitry to withstand an overcharge condition.

Over-Discharge Protection: Conducted on a fully charged sample to determine the device's ability to withstand an over-discharge condition; conducted with all discharge protection circuitry for both temperature and minimum voltage connected to prevent irreparable cell damage.

Imbalanced Charging: Determines whether an EESA with series-connected modules can maintain the cells/modules within their specified operating parameters if it becomes imbalanced.

Dielectric Voltage Withstand: Evaluation of the electrical spacings and insulation at hazardous voltage circuits of the electric energy storage assembly.

Isolation Resistance: Intended to determine that insulation adequately isolates hazardous voltage circuits from accessible conductive parts of the electric energy storage assembly and is non-hygroscopic.

Continuity: Evaluates the continuity of the protective grounding system of the electric energy storage assembly.

Temperature: A series of tests that verify that an electrical device can withstand the effects of extreme temperatures without causing a fire or explosion. These are some of the specific tests that are included in the UL temperature test:

High temperature: The device is exposed to a high temperature for a specified period.

Low temperature: The device is exposed to a low temperature for a specified period.

Thermal cycling: The device is repeatedly exposed to high and low temperatures.

Thermal shock: The device is suddenly exposed to a high or low temperature.

Failure of Cooling/Thermal Stability System: evaluates the electrical energy storage assembly's ability to withstand a cooling/thermal stability system failure safely.

Mechanical Tests:

Vibration: evaluates the electric energy storage assembly's ability to withstand simulated vibration that would occur over the life of the device.

Mechanical Shock: verifies that an electrical device can withstand sudden, forceful accelerations and decelerations without failing.

Drop: intended to evaluate whether a hazard exists when an EESA is subjected to an inadvertent drop during installation or removal from the vehicle.

Rotation: verifies that an electrical device can withstand continuous rotation without failing.

Crush: conducted on a fully charged electric energy storage assembly to determine its ability to withstand a crush that could occur during a vehicle accident.

Environmental Tests:

Thermal Cycling: determines the electrical energy storage assembly's ability to withstand exposure to rapidly changing environments, such as when the vehicle enters or exits a heated garage after being in a cold environment or during transport.

Immersion: verifies that the battery can withstand submerging in water without releasing harmful chemicals or igniting.

External Fire Exposure: determines an EESA's ability to prevent an explosion due to exposure to a simulated fuel or vehicle fire external to the electrical energy storage assembly.

Salt Spray: verifies that an electrical device can withstand exposure to salt spray without corroding or failing.

Thermal Runaway: simulates a thermal runaway event in the battery, which is a condition in which the battery cells heat up uncontrollably and can lead to a fire or explosion.

UL Safety Standards

Batteries must pass all required tests in order to be certified to a UL standard. This certification ensures the EV batteries meet minimum safety requirements, adding to consumer confidence and further adoption of EVs.

Some of the UL standards with requirements for EV batteries include the following:

UL 2271 – Batteries for Use in Light Electric Vehicle (LEV) Applications

UL 2271 is a standard for EESAs, such as battery packs and combination battery pack-electrochemical capacitor assemblies, intended for use in light electric-powered vehicles. It does not evaluate the performance or reliability of these devices.

UL 2580 - Batteries for Use in Electric Vehicles

UL 2580 is a standard for electric vehicle battery systems that covers the safety aspects of these systems' design, construction, installation, and operation. It specifies requirements and tests to help protect against electric shock, fire, mechanical, and environmental hazards. It also guides the proper handling, transportation, and recycling of electric vehicle battery systems.

UL 2596 - Test Method for Thermal and Mechanical Performance of Battery Enclosure Materials

This Test Method evaluates the thermal and mechanical performance of battery enclosure materials in response to stresses representative of thermal runaway of lithium-ion cells used in electric vehicles.

UL 9540 – Energy Storage Systems and Equipment

UL 9540 covers energy storage systems that receive and store energy to provide electrical energy to loads or the local/area electric power system when needed. The types of energy storage covered include electrochemical, chemical, mechanical, and thermal. The standard evaluates the compatibility and safety of various components integrated into a system.

UL 9540A – Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems

UL 9540A is a test method for evaluating thermal runaway fire propagation in battery energy storage systems. It was developed to address safety concerns identified by building codes and the fire service in the United States. The test methodology evaluates the fire characteristics of a battery energy storage system that undergoes thermal runaway.

This test method includes four hierarchal levels, all looking at different evaluation markers based on the level. These include the cell, module, unit, and installation levels.

Conclusion

EVs can reduce our carbon footprint and improve air quality in terms of tailpipe emissions when compared to internal combustion engine vehicles. However, it is essential to acknowledge and address the hazards associated with their use, such as battery fires related to thermal runaway and stranded energy, the chemical exposure linked to off-gassing, and chemical runoff due to the response effort to an EV fire. By enacting proper safety measures, such as manufacturing quality control, regular maintenance, proper training for emergency responders, supply chain and user safety education, and adherence to practical safety standards, these risks can be mitigated to help allow for the safe implementation and adoption of EV technology.

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