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TECHNICAL NOTES

Fire Hazard Assessment of Lead-Acid Batteries

Final Report by:

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Foreword

Several NFPA standards, such as NFPA 1, 75, 76, 111 and 855 address the fire resistance of large-scale battery deployments. Some, such as NFPA 855 request large-scale fire testing when installations exceed the maximum allowable quantities in the codes and standards. Lead-acid batteries have had a long history of use in the telecommunications industry, data centers, nuclear industries, power industries, among others. Since many of these battery chemistries are now being regulated by the same standards, a better understanding of the fire risks associated with lead-acid batteries was needed for use as a comparison to other battery chemistries.

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About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

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Fire Hazard Assessment of Lead-Acid Battery Chemistries

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Executive Summary

In recent years, lead acid batteries have been replaced by lithium ion batteries in many applications. This is a result of the lithium ion batteries having a greater energy density, efficiency, and lifespan as compared to lead acid battery chemistries. These batteries, however, are capable of storing large amounts of energy and often utilize a volatile or combustible electrolyte and thus are prone to fires and explosions. As a result, significant testing has been conducted to identify the fire hazards associated with lithium ion batteries. However, little testing has been performed on the lead acid battery chemistries. Thus, in this work, fire hazards associated with lead acid batteries are identified both from a review of incidents involving them and from available fire test information. From this, it is determined that lead acid batteries present low fire risks.

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Introduction

Lead acid batteries were invented in 1859 and were the earliest type of rechargeable batteries to be used in commercial applications. They consist of flat plates submerged in a dilute electrolytic solution containing sulfuric acid (H_2SO_4), with the anodes consisting of lead dioxide plates and the cathodes consisting of lead plates, as shown in Figure 1.

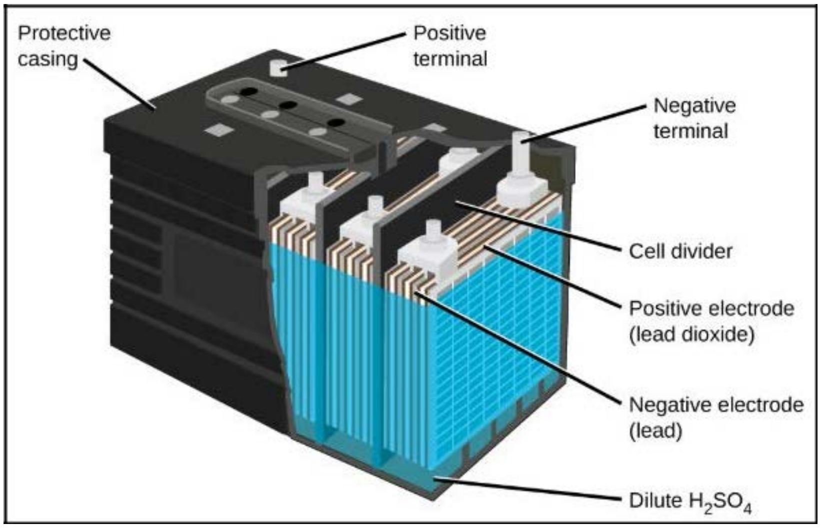

Figure 1: Lead-Acid Battery Diagram

In order for the battery to store energy, the sulfuric acid triggers chemical reactions within the plates in order to produce electrons, which generate the electricity[4]. As these reactions are reversible, the battery can be used for the duration of its life. The lead acid batteries are divided into two categories, flooded and valve-regulated lead acid (VRLA). In flooded cell batteries, there is an excess of electrolyte fluid, resulting in the lead plates being completely submerged. In VRLA batteries, however, the electrolyte is immobilized, with excess oxygen and hydrogen built up in the battery vented out with a vent or valve. Advantages and disadvantages of VRLA and flooded lead acid batteries are presented in Table 1.

Table 1: Battery Type Advantages and Disadvantages

Flooded Batteries		**VRLA Batteries**	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
-Less Costly -Longer Lifespans	-Possible Leakage -More Ventilation Space Required	-Electrolyte Spillage Not Possible -Little Maintenance Required	-More Costly -Do Not Tolerate Overcharging

Lead acid batteries are used in a wide range of applications, including automotive, uninterruptible power supply (UPS), telecom, electric bikes, and transport vehicles. In 2019, the global market for lead acid batteries was valued at $58.95 billion. Within this market, the VRLA segment held a 33.9% market share and the flooded battery segment held a 66.1% market share[10]. Automotive was the largest application segment in terms of revenue share. Within the US, there were approximately 279.6 million vehicles in use in 2019, with 93% of them using lead acid batteries, resulting in approximately 260 million lead acid batteries in automotive applications in the US.

In recent years, lithium ion batteries have become widely used as a result of having greater energy density, efficiency, depth of discharge, and lifespan as compared to lead acid battery chemistries. However, as lithium ion batteries can generate large amounts of energy and often contain a volatile or combustible electrolyte, they are susceptible to an increased frequency of fires and explosions. Because of this, much research has been conducted in recent years regarding the fire hazards associated with lithium ion battery chemistries.

Publicly available research on the fire hazards associated with lead-acid battery chemistries is limited, including resources such as fire test data and fire incident reports. Fire test data can be used to determine the potential for thermal runaway, defined as a thermal reaction where the internal heat generation exceeds the rate at which heat can be dissipated, leading to a thermal reaction such as fire. According to the available literature, VRLA batteries are more prone to thermal runaway than flooded lead acid batteries[5]. While this study did not investigate the effects of the battery materials, including the casing and battery design, this report focuses on identifying and analyzing the fire hazards associated with lead acid battery chemistries through a review of relevant fire incidents and results of fire testing.

Fire Incidents

In the first portion of this project, a review and investigation of fire incidents was conducted, with a total of 26 incidents identified and investigated. From these incidents, a total of 14 deaths and 12 injuries were determined to have occurred. The injuries include cuts, burns, eye damage, and permanent hearing loss. The incidents identified in this report occurred within the 40-year timeframe of 1979 to 2019. These incidents occurred around the world, though were primarily concentrated in the U.S. and Australia. Furthermore, these incidents occurred in both above ground locations and underground mines. The batteries involved in these incidents included both the flooded cell and VRLA types, and the batteries were encased in different types of materials, particularly the telecom grade fire resistant casing and the non-telecom grade casing. The incidents covered in this review consist only of those for which a report has been published. As such, this does not include all incidents that have occurred. Many more minor incidents, particularly those that have not resulted in injuries or deaths, have likely occurred that have not been reported. These include explosions associated with jump starting of automotive batteries.

The identified incidents occurred from lead acid batteries used in a wide range of applications, including both stationary and mobile devices. Stationary devices include battery banks, diesel emergency power source generators, and telecommunication power supplies, with 14 of these incidents having been identified. Mobile devices include cars, boats, and electric wheelchairs, with 12 of these incidents having been identified. A description of each of these incidents is located in the results section of this report, with detailed descriptions of three of these incidents below.

On May 25, 2007 a battery explosion occurred in a marine shop in Santa Ana, CA. During this incident, a 68-year-old boat repairman placed a 12 V marine battery on the floor of the marine shop near a battery charger and a customer's boat. The repairman then began to connect the battery charger to the marine battery when the battery exploded. The explosion then caught both the repairman and the customer's boat on fire[13]. The repairman attempted to extinguish the boat's fire despite being on fire himself. The repairman was then treated by paramedics before being transported to a local hospital, where he died shortly thereafter from his injuries.

On September 7, 2008 an electric wheelchair was unloaded from an airplane containing 229 passengers. When the wheelchair was placed on a vehicle, it burst into flames and was destroyed[17]. From investigation of the incident, it was determined that the battery, which was a gel-type VRLA 12 V battery, was the cause of the incident. Furthermore, it was found that the battery had not been disconnected prior to takeoff. This resulted in the battery short circuiting, thus initiating the fire.

On December 18, 2019 a battery fire occurred at the NRG power plant in Milford, CT. During this incident, a battery overheated that was located within a 250 V DC battery bank consisting of 50 lead acid batteries. This led to an electrical fault that resulted in a fire engulfing the battery bank[12]. The flames resulting from this fire were estimated to be 2-3 feet high, and firefighters utilized a dry chemical fire extinguisher to put out the fire. No injuries or deaths were reported as a result of this incident.

Fire Testing

In addition to investigation of incidents related to lead acid battery fires and explosions, fire testing of these battery chemistries has also been reviewed. In one set of these tests, three different types of VRLA (valve-regulated lead acid) batteries were tested. These were enclosed within telecom-grade case material, which is more fire-resistant than typical case material and is designed for use within the telecommunications industries. As the battery types and testing methods are confidential information, only a general description of the testing methods and results are described.

The tests consisted of applying short circuits for 1 minute and 24 hours to each of the three battery types, and determining whether fire, explosion, or leaking occurred. From the results of the tests, the three battery types conformed to applicable standards. For a different VRLA battery type, external short circuit testing was also conducted, with the results indicating that no fire or explosion occurred. In other tests, lead acid batteries were heated to temperatures of approximately 325 °C. This was performed to determine the gas emission rate of the batteries in the fully charged state over a range of temperatures in order to determine whether the batteries conformed to the applicable ventilation requirements. Furthermore, the tests were performed to identify whether the batteries would self-ignite and if thermal runaway would occur. From these tests, it was found that the batteries emitted HCl and SO_2, with low level emission occurring at temperatures near 125 °C. However, these lead acid batteries did not exhibit flammability during the tests and thus thermal runaway was not detected.

Additionally, the potential for thermal runaway within the lead acid batteries was identified and tested for each of the three types of VRLA batteries, with each battery type tested individually and assembled into strings. For the battery string testing, each string was exposed to ambient temperature and floated at the manufacturer-specified voltage, which was then increased at a constant rate until thermal runaway was detected. For the individual battery testing, the protocol was the same as that of the string testing except that the effective float voltage was increased at a lower rate. For each of the three battery types, it was determined that the batteries did not pose significant thermal runaway risk under typical operating conditions, as the voltages at which thermal runaway occurred were much greater than normal operating voltages. These conclusions are based on the results of these fire tests and thus may not be applicable for all lead acid batteries.

Results

Based on review of fire incidents and fire test data, the information is presented as follows. The stationary device incidents (involving diesel emergency power source generators, charging stations, power banks, power cable racks, etc.) are presented in Table 1, with mobile device incidents (involving cars, wheelchairs, boats, dozers, etc.) presented in Table 2. Lastly, the fire testing data is presented in Table 3. For confidentiality purposes, the specific test dates and battery models used in the fire testing are not included within this report, and are referred to as "Battery A, B, C, D, E, and F."

Stationary Device Incidents

Table 2: Stationary Lead-Acid Battery Incidents

Incident	**Date/ Location**	**Description**	**Injuries/ Death and Destruction**	**Battery Voltage**	**Size of Fire or Explosion**
Significant Incident Report No. 37	Reported 23, 1993 in Western Australia	-Serviceman was replacing a defective battery terminal when hacksaw being used came in contact with both terminals of battery causing an explosion	-Ruptured battery case damaged man's left eye	No information	No information
Telephone Exchange Fire	March 15, 1994 in Los Angeles, CA	-High current flow at one battery post ignited plastic casing on battery, with the fire spreading and igniting the other casings[8]	-Loss of 911, police, and fire comm. for 1 hour -3 workers injured from smoke inhalation	4160 V AC reduced to 480 V and rectified to 48 V. Battery bank involved 6 sets in parallel.	Fire engulfed batteries, smoke level approximately 3 feet above floor
Power Cable Rack and Battery Fire	March, 1995 in Idabel, OK	-Damaged cable insulation caused grounding of power cable, allowing discharge of batteries and ignition of battery stand (Power Cable Rack and Battery Fire, Idabel / Not Online)	-Loss of telecommunications service for 13 hours & all telecommunications equipment damaged	12 batteries connected in 48 V DC string	Fire covered 20 square feet of cable in racking as well as upper half of battery string

Battery Box Fire	September 12, 1999 in Denver, CO	-Box containing 2 rechargeable, lead-acid batteries caught on fire and was discovered during FedEx unloading[1]	-None reported	Not Mentioned (Assumed 12 V)	Box caught fire
Jim Walter Resource Mine No.5	September 23, 2001 in Alabama, USA	-Roof fall occurred in Section 4 near a battery charging station damaging the battery (which caught on fire) and releasing methane -Combination of methane gas and an ignition source caused 2nd explosion that propagated throughout mine[17]	-Initially 4 injured from first explosion -13 deaths	Two compartments with 64 V batteries (each battery had 32 cells of 2 V)	Explosion covered 7 sections (at least a mile of destruction)
Battery Package Fire	March 25, 2002 in Memphis, TN	-After an initial cargo flight, the package containing the battery/batteries caught fire at the FedEx sort facility in Memphis[1]	-None reported	12 V	Entire package caught fire
Battery Short Circuit and Fire	September 14, 2004 in Greenville, SC	-One battery was packaged so that its terminals were able to come into contact with metallic sensor tape that was packed with it, resulting in a short circuit and fire[1]	-None reported	12 V	Small fire surrounding package
Nasa IV&V Emergency Generator Battery Explosion	May 17, 2010 in Fairmont, WV	-A lead acid battery used to start a diesel emergency power generator exploded, spreading sulfuric acid near the generator[18]	-None reported	12 V	Explosion resulted in small amount of sulfuric acid around battery
Kahuku Wind Farm Fire	August 1, 2012 in Oahu, HI	-Fire occurred in the enclosed energy storage room containing 12000 lead acid batteries to capture wind energy -Lead acid batteries were sealed, “dry cell” type -Fire lasted for 13 hours and smoldered for 36 hours -Fire started near battery banks and spread[2]	-None reported	12 V (30 MW total battery energy storage)	Fire spread throughout warehouse, completely destroying building

Mine Safety Alert No. 280	2012 in Queensland, Australia	-Overcharged VRLA batteries produced hydrogen which vented into a room -Hydrogen and ignition source (likely battery charger) led to explosion[15]	-No injuries/deaths -Batteries were destroyed	Likely nominal 12 V based on battery type	Several feet around batteries
Battery Bank Fire at NASA Madrid DSN Complex	October 15, 2014 in Madrid, Spain	-Battery bank module consisting of 412 batteries in series caught fire[3]	-Loss of battery bank	12 V	Fire engulfed 4-5 batteries
Battery Explosion*	December 20, 2015	-Short-circuit of three 1.5 V batteries resulted in explosion[6]	-Severe injuries to thighs of victim	1.5 V	Small explosion
Montana Member County Road Shop*	February 13, 2019 in Montana	-The battery was originally outside in sub - 0 °C temp. -Worker let battery warm then slowly charged it -When battery didn’t charge, he wiggled one of the charging cables and the battery exploded	-Battery acid splashed onto worker who was wearing personal protective equipment (PPE), so no damages	No info	No information
NRG Power Plant Fire	December 18, 2019 in Milford, CT	-Batteries overheated, causing electrical short that resulted in bank of 50 lead acid batteries catching fire[12]	-Loss of battery bank	250 V DC battery bank containing 50 batteries	Battery bank burning with flames 2-3 feet high

* The “Battery Explosion” and “Montana Member County Road Shop” events were not specific on the purpose of the batteries. They were categorized as stationary incidents because the batteries were separate from the machine at the time of fire/explosion.

Mobile Device Incidents

Table 3: Mobile Lead-Acid Battery Incidents

Incident	**Date/ Location**	**Description**	**Injuries/ Death and Destruction**	**Battery Voltage**	**Size of Fire or Explosion**
Australian Car Battery Explosion #1	July 29, 1979 in Australia	-Motor yard worker was reading the oil dipstick and used a butane lighter to see -Worker held the lighter over the car battery, causing it to explode	-Battery acid splashed into both eyes and there was some skin damage	Likely 12 V car battery	No information
Australian Car Battery Explosion #2	March 30, 1980 in Australia	-32-year-old worker examined a truck battery using a butane lighter, causing the battery to explode	-Exploded battery lid caused battery acid skin burns and eye damage	Likely 12 V car battery	No information
Australian Car Battery Explosion #3	November 15, 1980	-Electrical engineer was tightening positive terminal on battery when he accidentally touched car body with spanner causing battery to be shortened -Shortening caused a spark that ignited battery	-Battery acid splashed worker's eyes and face	Likely 12 V car battery	No information
Australian Car Battery Explosion #4	April 10, 1981	-While connecting terminals the dead battery exploded and the cell plugs exploded	-Battery acid splashed the policeman's eyes and face	Likely 12 V car battery	No information
Automotive Battery Explosion	April 25, 1997 in Evans City, PA	-Vehicle salesman tested automotive battery with battery tester, creating a spark that resulted in an explosion loud enough to result in permanent hearing loss[11]	-Permanent hearing loss of victim	12 V	Small explosion surrounding battery

New South Wales Battery Explosion	Reported November 15, 2000 in New South Wales	-Employee failed to disconnect batteries from charging unit properly, allowing hydrogen gas to collect and cause an explosion when a spark occurred	-Employee sustained a cut on the head	12 V	No information
Mine Safety Alert No. 105 (Multiple Occurrences)	2003 in Queensland, Australia	-While jump starting flat batteries of truck, metal clips accidentally hit the truck causing a spark[16]	-Bruise on back of hand	Likely 12 V car battery	Very small, only a spark
Marine Battery Explosion and Fire	May 25, 2007 in Santa Ana, CA	-A boat repairman worked to connect a battery charger to a lead acid marine battery inside a boat shop and the battery exploded -The victim caught on fire and died[13]	-One death	12 V	Fire covered boat and victim
Electric Wheelchair Fire	September 7, 2008 in Manchester, UK	-Battery-powered wheelchair burst into flames as it was being unloaded from a passenger aircraft -Battery was gel-type VRLA[20]	-None reported	12 V	Fire engulfed wheelchair
Queensland 2017 Compilation Reports (Page 1)	December 2017 in Queensland, Australia	-Fire in a Cat D11T dozer engine bay was caused by a battery lead rubbing against hydraulic hose[16]	-None reported	12 V	No information
Car Battery Explosion in House	October 26, 2018 (no information on location)	-Writer was trickle-charging (had been doing this for weeks) a car battery when it exploded[19]	-No injuries -Damage to battery (wet black stains and black plastic all over)	No info but likely 12 V car battery	Fragmented pieces were scattered in workshop so explosion size was approx. the size of garage

Springfield 2 Car Fire	January 31, 2019 in Springfield Massachusetts, USA[9]	-2 individuals tried to jumpstart a car when both vehicle batteries caught on fire -Likely due to connection of terminals (electromechanical failure)	-No injuries or deaths -Although both cars caught on fire, they sustained damages	Likely 12 V car batteries	No information

Fire Testing Data

Table 4: Lead-Acid Battery Fire Testing Data

Battery/Type	**Battery Voltage/Test**	**Case Material**	**Results**
"Batteries A and B" Flooded Cell and Valve-Regulated Lead Acid	12 V Battery (Fully Charged and Off of Float Mode) -5000 sec. Test at 4 kW Heating Rate	Standard Material	-SO_2 and HCl Emitted Over Temperature Range Tested -No Fire
"Battery C" Valve-Regulated Lead Acid	12 V Battery -Short-Circuit Two Tests: 1 min. and 24 hr. Short Circuits	Telecom Grade (Flame Retardant)	Passed (No Fire)
"Battery D" Valve-Regulated Lead Acid	12 V Battery -Short-Circuit Two Tests: 1 min. and 24 hr. Short Circuits	Telecom Grade (Flame Retardant)	Passed (No Fire)
"Battery E" Valve-Regulated Lead Acid	12 V Battery -Short-Circuit Two Tests: 1 min. and 24 hr. Short Circuits	Telecom Grade (Flame Retardant)	Passed (No Fire)
"Battery F" Valve-Regulated Lead Acid	12 V Battery	Standard Material	Passed (No Fire)

Discussion

Based on the results of the incidents involving lead-acid batteries, a number of findings were obtained. Based on the limited literature, fire test data, and incident reports available, lead acid batteries have low risks as energy sources. This is based on the small number of incidents reported, indicating that the probability of incidents occurring is low, as well as the fact that that the majority of incidents investigated having had fairly minor consequences. In addition, the results of the fire testing support this statement, as no fires were observed in the tests. The limited data available shows that the aqueous electrolyte present within the flooded lead acid batteries inhibits the fire spread. This conclusion stems from the fact that the flooded lead acid batteries are involved in fewer documented incidents than VRLA batteries, indicating that flooded lead acid batteries are not prone to thermal runaway. For VRLA batteries, there is no way to replenish the water lost due to exposure to high temperatures and/or overcharging, making them susceptible to thermal runaway. Furthermore, the stored energy in the battery contributes to the fire severity, particularly when the batteries are connected in series. Based on the results of the short-circuit fire testing of batteries enclosed in telecom-grade casing, it inhibits the spread of these fires to additional batteries connected in series. This illustrates the usefulness of the telecom-grade casing in fire prevention and mitigation. Thus, these findings illustrate that the lead acid batteries are significantly less prone to fires than lithium ion batteries.

Conclusions

From a review of incidents and fire testing data involving lead acid batteries, it has been determined that lead acid batteries do not pose significant inherent fire risks as compared to lithium ion batteries. Inherent fire risks of lithium ion batteries involve the large quantities of energy stored within them as well as potential for thermal runaway if the battery is short-circuited or exposed to high temperatures. For lead acid batteries, a limited number of incidents have been documented, with a low number of injuries and deaths having resulted from these incidents. This suggests that lead acid batteries have low fire risks, which is further illustrated by the large number of lead acid batteries in use. Based on the results of the incident review and the fire test data, flooded cell lead acid batteries are less fire prone than VRLA batteries, and the telecom-grade casing on the batteries inhibits the fire spread.

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