Battery Energy Storage System Incidents and Safety: A Technical Analysis by UL

Energy Storage Systems continue to be deployed in increasing numbers, promoting improved grid performance and resilience, complementing renewable energy technologies, and empowering energy consumers. While the deployment continues to be largely safe and successful, a number of safety incidents have occurred around the world. This paper, developed by UL, provides a technical analysis of the work done to support safe energy storage deployment, and the reports recently issued on notable incidents.

See the following links for more information on:

- Executive Summary of the Underwriters Laboratories and UL Responses on Battery Energy Storage System Incidents and Safety
- Battery Energy Storage System Incidents and Safety: Underwriters Laboratories Standards Overview

Introduction: UL's Global Efforts for Battery Safety

UL has been a global leader in advancing safety of batteries and battery-operated products since the 1970s through research, testing, development of requirements, certifications, failure analysis and public education. As batteries have become increasingly more important parts of our lives and of the electrical infrastructure, UL's work to support safe deployment of batteries has also become increasingly important.

UL's first requirements for battery safety were developed by our experts more than four decades ago, ultimately laying the groundwork for the first consensus battery standard, UL 1642 for lithium batteries. UL has remained at the forefront of battery safety as the chemistries, technologies and applications have evolved dramatically. From the first comprehensive stationary battery safety requirements, to the first electric vehicle (EV) battery safety requirements, to requirements for safe repurposing of EV batteries, UL has been extremely active in applying our research and technical insights. Critical for safety of our energy infrastructure, UL also developed the world's first safety requirements for energy storage systems that led to the publication of Standard UL 9540. In response to concerns from the regulatory community to characterize fire hazards for energy storage systems and address a need for a test method to meet the large-scale fire test exceptions in the fire codes, UL also developed the first large scale fire test method for battery energy storage systems, UL 9540A.

UL has been able to stay at the cutting edge of battery safety through applying many years of experience with evaluating batteries and battery applications for safety and advancing that experience through comprehensive safety research. For example, UL 9540A was developed by UL fire researchers with input from industry, regulators and fire and explosion experts as well as other subject matter experts.

UL certification is based on rigorous investigations built on a foundation of strong safety science. The UL Mark on a product is a powerful identification that the product has been independently assessed by engineers and technicians to the applicable safety requirements, and a surveillance program established to audit ongoing production. At the time this paper was published, there have been no field incidents involving UL certified battery energy storage systems (BESS) or stationary battery systems. Specifying and using UL certification for safety is an important practical step in implementing BESS infrastructure that meets the safety expectations of the marketplace.

Field Incidents Involving Battery Energy Storage Systems

Unfortunately, there have been a number of safety incidents involving energy storage systems. Incidents involving lithium-ion BESS have resulted in significant damage, especially in Korea. There was one official Korean government report on the incidents in Korea that identifies root causes of the incidents. This report indicates a problem with the integration of the various parts of the system such as poor environmental controls, surges damaging safety controls, and controls from the various parts of the system that did not operate in a harmonized fashion. The field incidents involved systems in utility and industrial applications, these systems were installed in different environments with batteries from several different manufacturers.

There was also the tragic incident in Surprise, Arizona in 2019 involving a utility installation of a lithium battery system that resulted in severe injuries to first responders. Through public information that has come out after the incident, interested parties have considerably more information on the potential cause of the incident as well as details of the system construction, where it was installed, and the timeline of the event than what has been provided on the various Korean incidents. This body of knowledge includes the detailed report issued by the Underwriters Laboratories' Firefighter Safety Research Institute (FSRI) under a research project from the United States Department of Homeland Security.

Incident Reports

There are three publicly available reports thus far on the Arizona incident, from FSRI, DNV GL and Exponent, with recommendations provided by two of them. There was concurrence in the reports that the incident that injured the first responders was due to ignition of a combustible concentration of gas from the batteries. It was also evident that the actual fire damage was limited to one rack of batteries, although that one rack represented approximately 94 kWh of energy. The system had been in operation since March 2017, and from January 2018 until the time of the incident, it was being used to support solar energy generation resources.

These incidents involving lithium-ion BESS are unfortunate for the industry, public and other stakeholders. The incidents in Korea were numerous and significant enough that the government felt it necessary to become involved in the response. The incident in Arizona presented additional concern as it involved serious injuries to the first responders.

None of the BESS involved in any of these incidents in Korea or Arizona were UL certified. Although UL 9540 was first published in 2014, the APS system was not known to be evaluated to UL 9540 by any third-party certification organization. There was no report of UL 9540A testing conducted on the Arizona system or the Korean systems. It is also not known if the LG Chem battery system employed in the Arizona system had been evaluated and certified to UL 1973, but if so, it was not certified by UL. Of course, using requirements from established standards for safety as a basis for certification, particularly National Standards for systems deployed in the United States, is an acknowledged best practice.

It is also important for the technical community to review available information from incidents and leverage it to determine if there can be practical improvements to the standards and codes, and other practices involving the installation of energy storage systems. There were missing details especially in the Korean government official reports and notable discrepancies in the reports that have come out of the Arizona incident, which we will examine in this paper. However, that does not take away from the fact that they also contain some very useful information that should be taken into consideration for possible revisions to UL Standards and code development, as well as, product safety certification approaches, as applicable.

The Underwriters Laboratories' Firefighter Safety Research Institute (FSRI) report addressed the firefighter experiences during this incident. The review was funded through a grant from the United States Department of Homeland Security (DHS) Federal Emergency Management Agency's (FEMA) Assistance to Firefighters Grant (AFG) Program. The FSRI report had a very detailed account of step by step details and analysis of the incident from the point of view of the first responders. The FSRI report did not intend to establish a root cause of the incident but did provide several recommendations that might help firefighters and other first responders facing a lithium-ion BESS incident. One of the recommendations was to provide some type of early warning signal, perhaps sent from the battery management system, to a control that can be accessed remotely to provide a better understanding of the situation occurring within the BESS for those on the scene. This early warning system has been a topic of discussion during code and standard development meetings over the past years, but agreement has not been reached on a standardized approach. UL is establishing a task group to review this issue with the intent of generating a proposal for consideration by the STP for UL 9540 regarding early warning systems that could provide useful information to first responders and other stakeholders of impending BESS problems.

DNV GL wrote a report for Arizona Public Service (APS) that investigated data gathered at the Surprise AZ scene as well as testing data from several sources conducting forensic work and other analysis for APS on the incident. DNV GL reviewed the information provided by these third parties and reported its assessment of the root cause and provided proposals. DNV GL indicated that since the actual testing and forensic work was done by third parties, they cannot attest to the veracity or accuracy of the information. The DNV GL report indicated from their review "with a reasonable degree of scientific certainty" that the root cause of the incident was due to a single cell failure (Cell 7-2 of a module of rack 15) from metal deposition and abnormal dendritic growth of the cell leading to thermal runaway. The metal deposition was found in other cells taken from the BESS involved in the incident that were not burned as well as cells from a similar unit installed at another location.

Exponent wrote a publicly available report of their evaluation of the LG Chem battery involved in the incident, and research they conducted on the root cause analysis. The Exponent work was supported by LG Chem and the report is preceded by a letter from LG Chem's representative that expresses their concern with the DNV GL report and its conclusions.

Analysis of the Incident Reports

In analyzing the reports that have been published, UL notes some issues that highlight disagreement. UL also notes some issues that justify a response to correct inaccuracies or misinformation. These issues are summarized below.

Root Cause: The root cause finding of the DNV GL report was disputed in the Exponent report. The DNV GL report did not indicate what may have caused the metal deposition and dendritic growth within the cells, which had been in operation for over one year. Some level of these phenomena can be a natural result of aging of lithium-ion cells, but excessive metal deposition could point to stress being placed on the cells through improper charging or over-discharging, or could point to some problem with the cell construction. It would be beneficial to review actual data to show how this conclusion was derived, especially considering the Exponent report that rebuts this assumption and provides a data-based analysis for the rebuttal. DNV GL attended a presentation where Exponent presented their opinions and findings, but DNV GL does not agree with them.

Exponent conducted several tests to try to replicate the conditions noted in the DNV GL report and correctly indicated that the recovery of cell voltage after the initial drop is not what is experienced as part of cell thermal runaway. Exponent indicates that the cell separator has a ceramic coating, which would not be breached by the dendritic growth or metal deposition noted by DNV GL. Exponent brings up the possible cause as a double insulation fault perhaps due to arcing, possibly due to environmental conditions within the container. From their evaluation, Exponent rules out a single fault failure and posits a simultaneous two-fault occurrence. They indicate confidence that the failure was due to an external electrical event that caused arcing, noting that the investigation is not complete, and therefore a definitive root cause for the incident has not yet been identified.

UL has been following and studying the issue of dendritic growth since the widespread notebook computer battery recalls in 2005-2006. There were many discussions about metal deposition and dendrites as the cause of internal cell failure, but over the years, most of the field issues involving cells that UL has investigated were ultimately due to root causes of manufacturing quality control problems such as contaminants in the active materials, uneven coating of active materials, weld splatter, misplaced or missing insulation, switching out separators or electrolyte additives, bent tabs or damaged electrodes during the assembly, and damaged casings. There have also been numerous incidents involving insufficient protection controls in the battery management system and product. UL has not investigated any incidents involving lithium-ion batteries that were found to be due to metal deposition and dendritic growth.

Also, DNV GL indicates that a later report of the Korean incidents indicated that cell failure was a cause of many of the incidents. The Korean government report actually states the following: “Defects were found in some battery cells, and the simulation tests were performed, nonetheless, no short circuit inside the cell that could lead to the battery's own ignition was found. However, if the states where the defected battery is charged in a wide range and the full-charge state is maintained continuously, the possibility of fire due to its internal short circuit may be increased.”

The DNV GL report indicates that lithium-ion cells are fragile, which can be true; however, lithium-ion batteries generally have a low failure rate and good overall safety record, especially those tested and certified to applicable safety standards. Lithium-ion cells require a strong safety design that has been tested to ensure it is adequate for the particular application, and they require stringent manufacturing quality control as many field incidents have been the result of manufacturing problems. Even with good design and manufacturing quality control, the cells cannot protect themselves, so sufficient safety controls and protections are vital to prevent abuse of the cells. A single lithium-ion cell, especially one that is rated 63 Ah and under a thermal runaway condition, can result in propagation throughout a module and a whole rack. UL has witnessed this with the UL 9540A testing conducted over the past years.

One issue noted from the Exponent report is that containerized energy storage systems installed outdoors that incorporate heating, ventilation and air-conditioning (HVAC) systems may not necessarily be assumed to provide a controlled environment within the container. This should be considered when determining the suitability of electrical insulation and spacings within the container. The Arizona BESS was a walk-in unit that had HVAC systems and employed a clean agent fire suppression system. However, it was not provided with explosion control as would currently be required in accordance with NFPA 855 for a lithium-ion walk-in system.

Safety Standards: The DNV GL report criticized the UL consensus Standards that address this equipment. The conclusions offered are specious and editorial, as the system was evidently not evaluated to UL 9540 or tested in accordance to UL 9540A. The conformance of the LG Chem battery systems used in the Surprise incident to UL 1973 is also unknown. There is also a concern about adequate understanding of the requirements in the standards, which have supported an excellent safety record in the field. Criticizing safety standards that were not used for assessing the equipment involved in an incident is without technical merit. However, field experiences are useful in looking forward to potential enhancements for the future.

DNV GL’s two main criticisms of UL Standards are that (1) they do not evaluate cell-to-cell thermal runaway and (2) they do not evaluate combustible off gassing.

UL 1973 has included a propagation test assessing cell-to-cell thermal runaway for stationary batteries from its first publication. This Single Cell Failure Design Tolerance Test does not preclude the spread of one failed cell to another but does not allow fire external to the enclosure or explosion. This is similar to other propagation tests such as those in IEC 62619 and in RTCA DO-311A, for example. For these tests there can be propagation to other cells within the battery, but it needs to stop within the enclosure and cannot propagate outside. The current requirements within UL 1973 were the result of work of a special task group to improve the clarity of the test procedure. The test has never indicated that the failure must stop at the cell that was failed, if it could be demonstrated that cascading beyond the device under test (DUT) enclosure would be prevented (e.g., module-to-module). UL 1973 does not have construction requirements for physical spacing between cells or for heat transfer limiting materials (e.g., insulation, intumescent materials, etc.) around cells, since the test allows the test sponsor to determine if such engineering approaches are necessary. The battery design including cell spacing and any protections to prevent excessive heat transfer is evaluated through testing under normal and abnormal conditions, including the initiation of a cell failure within the battery. UL 1973 enables manufacturers design freedom rather than dictating a particular construction approach.

UL 9540 does not include a specific propagation test for energy storage systems because it references UL 1973 mandatory battery requirements. In the 2nd edition of UL 9540, UL 9540A is referenced to evaluate thermal runaway propagation and characterize resulting fire and explosion hazards, if any, for BESS. A BESS appropriately designed and evaluated today will have the UL 1973 propagation test conducted on the battery system and if necessary, will be subjected to UL 9540A large scale fire testing. The UL 9540A test indicates that once propagation is initiated within a module, the installation shall be provided with sufficient protection to safely contain it. As in UL 1973, this approach enables manufacturers to pursue designs that mitigate thermal runaway, fire and explosion hazards within the unit or by protection systems provided within an installation. The goal of UL 9540A, unlike UL 1973 single cell failure design tolerance test, is to achieve propagation within a module in order to determine if the overall protections are sufficient to meet the fire and explosion requirements of the model codes.

With this in mind, the UL Standards do not prescribe performance that eliminates cell-to-cell propagation but do address the critical practical hazard: consequences of propagation into an event that is not contained within the unit. The current standards effectively evaluate the batteries response to a cell failure event and evaluate the BESS response to propagation. The need to mandate a specific design approach, in lieu of the effective performance-based assessment that allow appropriate alternative approaches to be validated, has not been substantiated.

DNV GL criticizes UL 9540A for not specifying a specific number of cells to fail during the module and subsequent unit and installation level test. There have been extensive discussions on this topic with various stakeholders, including STP 9540, and the current consensus requirement in UL 9540A is the result. The number of cells to be failed is not a straightforward determination, as DNV GL suggests. It is important to understand that the standards seek to address an innovative and dynamic array of technologies which include different chemistries, cell construction formats and physical size, cell safety features, electrochemical capacities, physical arrangements within modules and units, and module and unit safety features such as thermal barriers or reactive materials (e.g., phase change or intumescing). UL 9540A requires that the testing laboratory test one or more cells to determine if propagation is possible: "*A sufficient number of cells shall be forced into thermal runaway to create a condition of cell-to-cell propagation within the module*." It is the responsibility of the test laboratory to determine through construction review and cell level test data, the number of cells required for testing, and demonstrate clearly with data that propagation is not possible in cases where cell-to-cell cascading cannot be achieved.

With respect to DNV GL's conclusion that the UL Standards do not evaluate flammable off-gassing from batteries, UL notes that UL 1973, UL 9540, and UL 9540A all address off-gassing. From its first publication, Section 9 of UL 1973 addressed the concerns of flammable off gassing during testing. UL 9540 references UL 1973 as a mandatory requirement rather than replicate battery specific testing, and also includes in Clause 22.2 a statement "*Electrochemical ESS which are not addressed in 21.1 and which are dependent on mechanical ventilation as a protection measure against emission of flammable gas that can occur during fault conditions to prevent hazardous gas concentrations within the system, shall be equipped with a fault detection system that activates the mechanical ventilation in a manner which prevents the LFL from exceeding 25% in any nonhazardous area/zone within the ESS."* In addition, the 2nd edition of UL 9540 references UL 9540A, which requires extensive gas capture and analysis of gases that vent from cells at the cell level test and that emit from the BESS during the pre-flaming and flaming periods during each subsequent level of the testing.

The UL 9540A test method, starting at the cell level, captures the gas venting from the cell when it is driven into thermal runaway. The typical method used to accomplish thermal runaway for lithium-ion cells is a thermal ramp using an externally applied thin film heater. The cell is failed in a volume that has been made inert to prevent burning of these gases. The total volume of the vented gas, identification of specific constituents that make up the gas, and the volumetric concentration (vol-%) of each constituent is identified. This gas composition is tested to determine its lower flammability limit, its maximum closed vessel deflagration pressure (P_{max}), and its burning velocity. The results of these tests characterize the explosibility of the gas composition. At the module, unit and installation test levels, the volume of the gases released by the system are measured to account for the amount of product involved in thermal runaway and pre-flaming and flaming conditions. The explosibility properties in combination with the volume of gas release constitute fundamental inputs that enable qualified professionals to design deflagration mitigation. UL 9540A also includes information in Annex A that provides guidance on how the gas information is to be used to determine suitable explosion protection, including reference to NFPA 68 and NFPA 69. Both UL 1973 and UL 9540A indicate that evidence of explosion is not an acceptable outcome for testing. The statement that UL 9540A does not address the explosion hazard of thermal runaway is patently inaccurate. The scope of UL 9540A indicates "*The test methodology in this standard determines the capability of a battery technology to undergo thermal runaway and then evaluates the fire and explosion hazard characteristics of those battery energy storage systems that have demonstrated a capability to undergo thermal runaway."* The evaluation for explosion hazards is under the scope of the standard. This statement has been included since the first publication of UL 9540A in November 2017.

After our review of the incidents, UL believes that if the systems involved in these incidents had been evaluated to safety standards, including UL 9540 and UL 9540A, the potential for hazardous propagation due to cell thermal runaway would have been identified and mitigated. This underscores the importance of using the established safety standards as a basis for safe deployment of technology.

Energy Storage System Standards Evolution

UL has been actively addressing safety of batteries and energy storage systems for many years. This includes publication of requirements which led to UL 1973 for stationary batteries in 2010; publication of requirements which led to UL 9540 for energy storage systems in 2014; and publication of requirements that led to UL 9540A in 2017. These efforts laid the groundwork for subsequent consensus National Standards for safety published for both the United States and Canada, laying a foundation of safety for these rapidly emerging technologies.

Prior to the incidents in Korea and Arizona, there had been, and continues to be, evolution of the UL Standards addressing battery systems. One example of evolution is what is referred to as the "single cell failure design tolerance test". This propagation test, which was included in both UL large format battery standards from their first publication, had always been designed as a single cell failure test considering replicating of potential known failure mechanisms. When UL became aware of other testing organizations applying the test method in a manner so that more benign results might occur, UL took action to enhance consistency and promote appropriate rigor of testing. UL established a task group of experts, including representatives from a range of interests including industry, US National Laboratories, users, and UL research staff to develop what is currently published as the single cell failure design tolerance test.

In terms of potential hazardous off-gassing from batteries, UL's large format battery standards, such as UL 1973, have always had the requirement to determine if there is combustible off gassing and toxic off gassing during the battery abuse tests. Exposure to external fire is additionally addressed in UL 1973 and is based upon the type of testing that evaluates enclosures for brush fire exposure as outlined in the Telcordia GR-487-CORE standard used in the telecommunication industry.

UL 9540, in addressing safety of multiple types of energy storage systems, references UL 1973 as mandatory battery requirements. Before there was a specific installation standard or much established in the way of fire safety criteria for battery energy storage systems, the first edition of UL 9540 referred to the fire safety guidance documents NFPA 550 and NFPA 551. These references, although still useful guidance documents for conducting an analysis to address fire hazards in an installation, were replaced in the 2nd Edition to reference NFPA 855 after its publication to specifically address requirements for fire protection design of the energy storage installation. In addition, UL 9540 2nd Edition references the UL 9540A large scale fire testing method. It requires that any system where large-scale fire testing is needed (due to size or installation details) must be subject to UL 9540A testing to evaluate the safety of the proposed installation. For example, the energy capacity of a nonresidential system is limited to 50 kWh in both NFPA 855 and UL 9540, unless UL 9540A testing has been conducted validating the safety of the planned installation or unless the system is limited to remote outdoor installations. UL 9540 installation instruction requirements including limits on separation distances and clearances to exposures such as three-foot minimum spacings between BESS or between BESS and walls, unless UL 9540A testing is conducted to validate smaller clearances and separation distances.

There were some significant changes to the safety analysis and functional safety criteria of UL 9540 2nd Edition, including defined minimum safety levels for those referenced functional safety standards that rely upon component and circuit reliability analysis rather than single fault conditions. These changes were implemented to address inadequate rigor of functional safety evaluations of systems by other organizations using UL Standards. Additional language was also added to emphasize the importance to consider the coordination of controls for different parts of the system to accomplish reliable safety outcomes. These changes to UL 9540 stem in part from the Korean government report as this being an issue in some of the incidents there. This need to evaluate the safe coordination of the various controls of the energy storage system has always been a criterion of UL 9540, but UL felt that stronger language to emphasize this concern was appropriate and the STP concurred. A new section on EMC testing was also added to ensure that this critical environmental evaluation is addressed. UL has always included consideration of electromagnetic compatibility (EMC) of circuitry involved with functional safety as part of our reliability evaluation of electronic controls. However, there are several global standards used for functional safety and some, such as IEC 61508, do not include mandatory EMC testing. UL proposed including EMC testing to eliminate a potential loophole with certain standards if an organization was using functional safety standards. This change was also made in part as a result of the report of the Korean incidents where some had been the result of protection controls damaged by surges within the system.

As previously noted, criticizing safety standards when the safety standards were not even used for the systems involved in an incident is illogical. Besides the fact that the system in question was not evaluated to either UL 9540 or UL 9540A, UL must note that the versions of the UL Standards referenced in the DNV GL report were outdated, demonstrating a lack of understanding of the standards framework in the critique.

UL's review of the incidents and reports was undertaken to determine if it is feasible to develop proposals to improve the UL Standards. UL will be looking to form task groups and/or submit proposals on several topics:

- Detection and Alerting: The ability to use embedded sensors and detectors to communicate safety-related information to first responders and others will be reviewed again. UL plans to establish a task group to review the possibility to define requirements for identification and communication of safety status or attributes that can minimize the risk of fire, explosion or injuries.

- Explosion Control: Ventilation is addressed in 22.2 of UL 9540. NFPA 855 now has a section on explosion control for indoor installations and walk-in systems. The current criteria of NFPA 855 would require systems like the Arizona system to include explosion control in accordance with NFPA 68 or NFPA 69 unless a large-scale fire test indicates that it is not necessary. UL is developing proposals to closely match this criterion for these walk-in container and similar systems to address this issue. Additionally, UL has ongoing research projects looking at these issues for continued enhancements to BESS fire safety.
- Conditions in Containerized Systems: As noted in the Exponent report, containerized energy storage systems installed outdoors that incorporate heating, ventilation and air-conditioning (HVAC) systems might not reliably provide a controlled environment within the container. This should be considered when determining the suitability of electrical insulation and spacings within the container. UL will be reviewing proposals addressing this issue that can be considered by the STPs for UL 1973 and UL 9540.

Conclusion

UL has been, and remains, focused on advancing safety science to support the safe and sustainable deployment of battery technologies and energy storage systems. The established UL requirements and Standards provide a sound foundation for diligently addressing safety of these technologies, and UL encourages the use of the National Standards for safety as a proactive measure of diligence and establishing confidence in compliant products brought to market. While UL continues to actively support further development of safety requirements, all interested parties are encouraged to make specific proposals for practical advancement of energy storage safety. The safety incidents that have occurred are unfortunate but can catalyze the energy storage community to collaborate toward finding new solutions leveraging lessons from incidents, application of technology, and innovative approaches. This effort is needed to accomplish the full promise of energy storage technology, and UL will continue our work to support that imperative.

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