COMPLIANCE WITH CODES AND STANDARDS RELATING TO LITHIUM-ION BATTERIES: A MANUFACTURER'S PERSPECTIVE

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Abstract
For several years starting around 2009, deployment of lithium-ion (Li-ion) energy storage systems (ESS) proceeded largely unencumbered by codes and standards. More recently, however, codes and standards bodies have been racing to catch up with deployments. These developments have taken on increased urgency in light of numerous incidents, including battery fires in South Korea and an explosion at a facility in Arizona that left firefighters injured.

We have seen several standards issued and updated by Underwriters Laboratories (UL) and more stringent storage-related requirements built into US fire codes. The fire-code requirements have now been consolidated in NFPA 855, Standard for the Installation of Stationary Energy Storage Systems, with the intent of making compliance with that standard mandatory in future releases of the fire codes. At the same time as the national picture is becoming clearer, we are starting to see the appearance of even more restrictive state-level requirements, as demonstrated by modifications to the New York State Fire Code.

This paper provides an overview of the development of these codes and standards, and the challenges faced by manufacturers having to address this rapidly evolving situation. These challenges are exacerbated by recent trends to products with significantly higher energy density. The influence of these documents on system design is discussed, particularly in relation to fire-suppression systems (FSS).

Introduction
The first containerized Li-ion ESS was shipped around 2009, and by 2018 global deployments of such systems had reached 17 gigawatt-hours, according to Bloomberg New Energy Finance[1]. While those early deployments had to meet generic electrical and fire codes, there were no standards or codes that covered the specific hazards associated with this battery type in large stationary installations. The closest anything came to a chemistry-specific safety standard was the cell-level requirements of UL 1642[2], which was written with portable cells in mind.

There was inevitably a lag between the growing number of ESS deployments and the issuance of safety standards to regulate them. UL 1973[3], which is not chemistry-specific, was first published in 2013 and it was not until the second edition was released in 2018 that it really addressed the safety issues associated with Li-ion. On the other side of the Atlantic, it was not until 2017 that IEC 62619[4] was published.

There have been several papers presented at Battcon[5, 6, 7, 8, 9] to cover the evolution of codes and standards relating to Li-ion batteries, and the reader is referred to those papers for background information. The intent of this paper is to give examples of how manufacturers are addressing the rapidly changing regulatory landscape covering large-scale Li-ion ESS. In addition to UL 1973, the most relevant standards for this work are NFPA 855[10] and UL 9540A[11], relating to large-scale fire testing. (The fire codes will either mandate NFPA 855 compliance by reference or will incorporate very similar requirements.) There is also a system-level standard, UL 9540[12], covering the battery, power conversion system, and controls (not directly related to the battery-only scope of UL 9540A), but that standard does not impose significant battery-level testing requirements over and above UL 1973.

Increasing energy density – a double-edged sword

As ESS deployments have shifted to multi-hour applications such as replacement of peaking generation, system footprint has become increasingly important, causing containerized Li-ion battery systems to be designed with increasing energy density. Figure 1 shows the increase in energy over time for containerized Li-ion battery systems offered by the author's company. All systems use Li-ion chemistry based on nickel oxides, including lithium nickel-cobalt-aluminum oxide (NCA) and lithium nickel-cobalt-manganese oxide (NMC).

2012 – 0.6 MWh **2015 – 1.0 MWh** **2020 – 2.5 MWh**

Figure 1. Evolving energy density in 20-foot containerized systems

The earlier container designs included relatively small modules incorporating thermal barriers between large cylindrical cells, and those barriers were effective at preventing cell-to-cell propagation of a thermal runaway event. A standard fire suppression system (FSS) using a clean agent, Novec 1230, is installed to handle any electrical fires that may occur, and the cooling effect of the Novec provides an additional safety margin against propagation. For the latest container design, the aim was to maximize the installed energy using close-packed pouch cells. That aim was certainly achieved, but it led to complications with fire suppression.

Figure 2 shows the setup for initial fire testing with the new container. Thermal runaway was initiated in one of the modules. There was propagation within that module, leading to a fire. The FSS triggered the release of the clean agent and the fire was extinguished. However, there was evidence that thermal runaway was continuing to propagate between cells and eventually between modules, and after approximately 90 minutes the fire reignited. The local fire department, which had been present for the test, extinguished the fire with water hoses, but all modules were lost.

Figure 2. Initial fire testing

Quantifying FSS effectiveness

It was obvious from the intervention of the fire department during the initial testing that water was an effective fire suppressant, but our engineers wanted to perform testing to understand the cooling efficiency of each of the fire suppressants. Figure 3 shows the test setup they used, with three blocks of cells, each with five 17.5 Ah pouch cells in parallel, and the clean agent FSS. Thermal runaway was initiated in the center cell block using a heater between cell 1 (lowest) and cell 2. The FSS was triggered using the normal sensing.

Figure 3. Test setup with three cell blocks and Novec FSS

Figure 4 shows the aftermath of the Novec test. There was clearly propagation within the initiating block, but the adjacent cell blocks remained intact. Figure 5 shows the temperature behavior during the test. The legend designations ‘Event *x*-*y*’ refer to the location of temperature sensors in the center block, between cells *x* and *y*. So ‘Event 1-2’ refers to the point of initiation, and full thermal runaway was suppressed between cells 3 and 4. The cell blocks on each side remained well below the critical temperature of around 120°C.

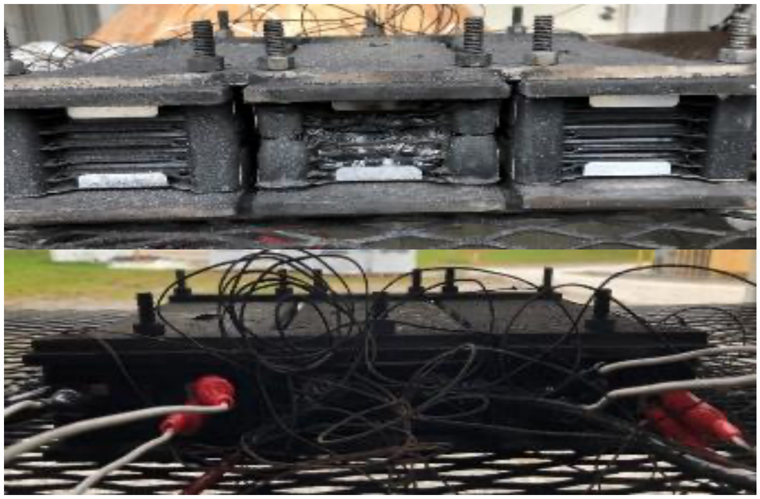

Figure 4. Aftermath of clean agent test

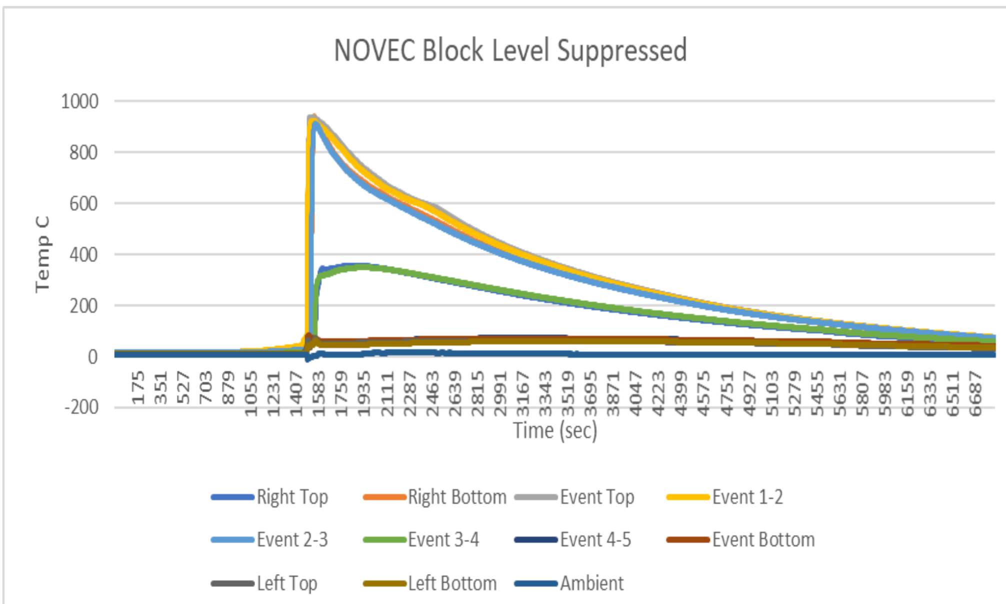

Figure 5. Temperature graphs for clean agent test

Various arrangements were tested for a secondary water FSS. It was found that ceiling-mounted sprinklers were not fully effective because of the close-packed module arrangement. Directing water at each module was found to be the best option, and the heat absorption of the water was superior to that of the clean agent. This effect is shown in Figure 6, with the test results plotted on an equivalent timescale. Where the clean agent took over an hour to bring the cells in thermal runaway down to 120°C, water achieved the same reduction in around 10 minutes. This result means there would be much less opportunity for propagation within the module.

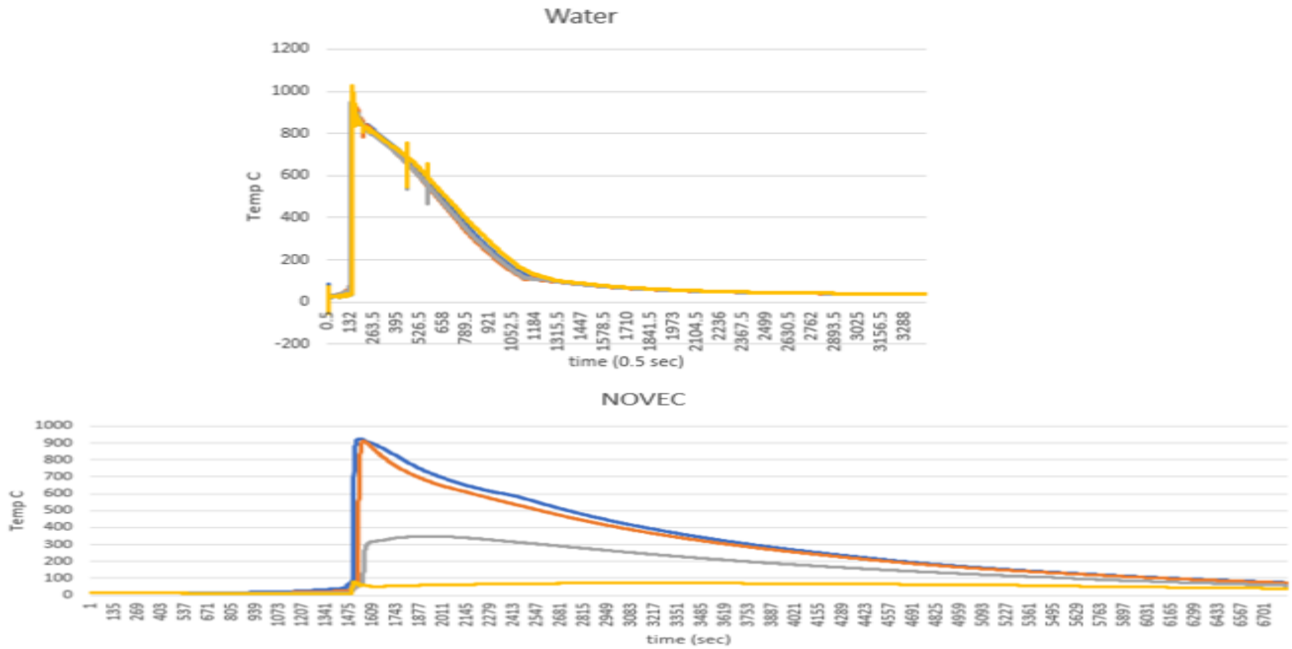

Figure 6. Comparison of water and Novec heat absorption

The effectiveness of the water FSS can be seen in Figure 7. Thermal runaway was initiated towards the front (left) of the lower module. The water FSS actuated after about 30 seconds and the fire was fully extinguished in just over 12 minutes. The picture shows that thermal runaway propagated through several rows of cells, but the rear three rows remained intact, as did the module above.

Of course, the disadvantage of the water FSS is that all modules would incur water damage and would need to be replaced. If there were a fire initiated in a component other than a battery module, it is quite likely that such a fire could be fully extinguished by the clean agent FSS and there would be no need to actuate the water system. The preferred solution is to allow first responders to make an informed decision on whether to trigger the water FSS. Initial shipments of the new system have incorporated a plug-in point for a fire hose, along with an external display panel showing the ambient temperature in the container. Fire department personnel have been trained and provided with documentation to flush the container with water only if they see an ongoing temperature increase in the container.

Figure 7. Results of water FSS test, showing initiating module (bottom) and module immediately above (top)

It is doubtful that a system with discretionary activation of the secondary FSS will be acceptable to all authorities having jurisdiction (AHJs). To achieve the necessary Listing, it is likely that the water FSS will need to be actuated automatically.

Evaluating the need for large-scale fire testing

NFPA 855 includes stringent spacing and maximum-energy limitations for Li-ion batteries, but these requirements are directed towards buildings with people present. If it is desired to bypass these limitations, the remedy is to show results of UL9540A testing to the AHJ and seek a waiver (because there is no pass/fail under UL9540A it is up to that individual's judgment to issue the waiver, but that's a separate problem). Under NPFA 855 a dedicated outdoor energy storage structure (a container or similar) is exempt from the code requirements if it is more than 10 feet from a building, road, walkway, or anywhere else people are likely to be. However, under a new modification to the New York State fire code[13], that distance has ballooned to 100 feet, and getting closer requires submission of UL9540A test result to the AHJ. The original intent was for UL9540A to be required in more exceptional cases (at least for most ESS), but now it is pretty much mandatory. Fortunately, compliance testing under UL 1973 can be augmented with some additional metering to meet the requirements of UL 9540A at the same time, so manufacturers can avoid the cost of two separate tests. Nevertheless, it is estimated that full compliance testing of a new battery system cost about a million dollars.

Product evolutions in response to codes and standards

The rapid development of codes and standards relating to Li-ion safety is causing manufacturers to rethink their approaches to product design. The fire-suppression systems described in this paper are active safety features, meaning that smoke and/or fire must be sensed and then the mitigation measures triggered. The probability of one of these systems failing is very low, but it is non-zero. The approach has therefore been to require spacing between containers, such that complete combustion of one container will not cause propagation in adjacent containers.

Rather than continuing this approach and emphasizing the highest possible battery energy in an ISO container, the incorporation of passive safety features to eliminate propagation, even if this reduces energy density, could be a better solution. The current safety spacing, at 10 feet (3 meters), is larger than the container width, so minimizing that spacing would have a major impact on footprint at the system level.

Until the last year or so, Li-ion chemistry in ESS mirrored that of electric vehicles, with most using NMC material because of its higher energy density, and fewer systems using lithium iron phosphate (LFP), which while having a lower cost, requires more volume for the same energy. There has recently been a wholesale shift to LFP, driven not just by lower cost, but a more holistic view of system-level safety and footprint.

With LFP cells it is possible to minimize cell-to-cell propagation of thermal runaway within a module, and to avoid module-to-module propagation, even without aggressive fire suppression methods. This improvement makes it possible to eliminate the safety clearance requirement and favors a change from ISO containers, with their requirement for all-around maintenance access, to closely packed cabinets with front access only. This closer packing more than makes up for the lower energy density of LFP, and provides a smaller system-level footprint.

It would be prudent for these newer cabinets with LFP chemistry still to include the capability for water-based fire suppression, but successful fire testing without the use of water would allow use of those systems at the discretion of the local fire department, using a plug-in for a fire hose.

Looking to the future

In addition to system design approaches, there are ongoing efforts to Improve lithium chemistries. Short-term developments are focused on safer electrode materials and non-flammable electrolytes for Li-ion batteries, while the longer-term goal is to develop solid-state lithium chemistry, which promises to be both much more energy-dense while also being significantly safer than today’s technologies.

The industry is rife with announcements from startup companies about the imminent deployment of solid-state designs in electric vehicles. The reality is that these new products are not likely to appear on production vehicles until 2025 or later. Furthermore, the more aggressive cycling required for batteries in ESS energy-shifting applications will likely delay deployment of solid-state chemistry in those systems until the end of this decade.

Conclusions

The recent development of new codes and standards relating to Li-ion systems has been rapid, and, in some cases—such as maximum energy and spacing requirements—rather arbitrary. This has imposed challenges in system design and very significant costs for manufacturers to achieve compliance. Ultimately, though, it seems likely that the new requirements will drive a change in design philosophy, emphasizing passive safety features and improved functional safety for ever-larger energy storage systems.

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