UL9540A LARGE SCALE FIRE TESTING RESULTS FOR SODIUM NICKEL CHLORIDE BATTERIES USED IN STATIONARY ESS APPLICATIONS

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Abstract
Sodium Nickel Chloride batteries have been commercially deployed and safely operating in stationary backup and Energy Storage System (ESS) applications for the last decade. Recent changes in fire codes, in particular the NFPA 855, has driven energy storage device manufacturers to perform large scale fire testing to the UL 9540A test method in order to provide additional data to the Authorities Having Jurisdiction (AHJs) to gain exemptions to the new requirements such as maximum rated energy in a control area, spacing, and clearance of products. This paper will present the results of the testing from a manufacturer's perspective, highlighting challenges and successes relative to compliance and/or obtaining exemptions to the NFPA 855.

Introduction
In recent years, municipal fire protection and code enforcement personnel have been challenged with catastrophic events when energy storage systems, in various applications, have failed, causing damage to structures, injuries to first responders, and loss of services. In many cases, the underlying root cause is levied on the battery technology, and this has caused concern that all battery systems have an inherent risk that increases in proportion with the amount of energy stored or the technology deployed. These events and further concerns have generated a demand for a new standard that puts requirements on energy storage system installations.

In response, The National Fire Protection Agency (NFPA) has developed the NFPA 855 Standard. This new standard sets a high bar in terms of compliance, which in many cases, will make a positive safety impact on the industry. As a result, the battery industry has been unsettled by the changes required to be compliant with this new standard. In many cases, these requirements are completely new to established energy storage technology manufacturers and also pose a significant challenge for any emerging or alternative technologies to address.

The manufacturer's major challenge includes NRTL (Nationally Recognized Testing Laboratory) testing to gain the referenced listings and large-scale fire testing to provide data to prove to the AHJ that installation of the proposed size (energy level in kWh) will not cause an increased risk of fire conflagration in operation or in fault. This is a major endeavor for an industry that has never been required to do this level of certification and testing on their products in the past.

This document intends to describe the high-level points in the codes and standards that drove the need for large-scale fire testing, which was new to their industry and products, and how the manufacturer addressed them. This document is not meant to be a comprehensive study of the standards or codes, its purpose is to describe the requirements and challenges that FZSonick, the manufacturer of sodium nickel chloride batteries, faced and how they were addressed.

Minimum thresholds that force standard compliance

The NFPA 855 requires any energy storage system (ESS) with an energy level greater than the threshold level in a single control area to be compliant with the standard to mitigate hazards associated with ESS installations. This means all but the smallest of systems installed in most stationary applications will be impacted. All common commercially available electro-chemical storage technologies have been included in this standard so in many cases the requirements are similar regardless of the technology being installed.

The threshold quantity for applicability can be summarized as follows:

- Installations in most locations other than regulated electric and telecommunications utilities will need to be compliant if the energy level installed is greater than the threshold in Table 1.3 of the standard.
    - 70kWh for Lead-acid and Nickel battery technologies (Nickel includes nickel-cadmium (Ni-Cad), nickel-metal hydride (Ni-MH), and nickel-zinc (Ni-Zn)
    - 20kWh for Lithium-Ion, Sodium Nickel Chloride*, and Flow batteries.
    - 10kWh for any technologies not specially listed.
    - 1kWh for residential battery installations regardless of technology.

As an additional note, in Section 1.4 the standard DOES NOT require retroactivity on systems installed before the effective date of August 25, 2019, but, it DOES give an AHJ the authority to consider retroactivity to any or all parts of the standard on systems that have been installed before the effective date if they represent an unacceptable degree of risk. Though this statement may not directly affect the manufacturer of ESS products it does have the potential to have a large impact on end-users and/or operators.

General requirements when applicable

Section 4 of the standard has the general requirements for all ESS installations once the code is deemed applicable by exceeding the energy levels discussed above. These are further modified by the technology-specific requirements called out in the sections detailing them, which for electrochemical storage is in Chapter 9.

Some of the general requirements in the standard that may impact the battery manufacturer are:

- Product listing to a referenced UL Standard by an NRTL
- Large scale fire test data to UL 9540A test method
- Support for Hazard Mitigation Analysis
- Requirements for documentation
    - Operations manuals
    - Maintenance requirements
    - Theory of operations, with recommendations of best practices
    - Training manuals
    - Commissioning plans
    - Emergency and decommissioning plans

Some of the above are not necessarily new or additional items that have been requested, but the difference is now it can be required by code, and therefore enforceable by law.

* *The Maximum Rated Energy (MRE) for sodium nickel chloride has recently been increased to 70kWh in the draft of the next edition, primarily due to the results of the UL 9540A testing performed by the manufacturer and summarized in this document.*

There are other requirements that will impact the end-user. These may or may not directly affect the manufacturer of ESS products but will most certainly present additional challenges in most markets.

For example, some of the general requirements in the standard that may impact the end user are as follows:

- Detailed construction documentation
- Hazard Mitigation Analysis
- Emergency procedure planning
- Additional signage
- Maintenance, testing and events logging
- Potential Retroactivity on existing systems

Section 4.6 places a 3 ft (914mm) spacing requirement from any other groups or walls when groups of greater than 50kWh each are installed. The utilities get a exemption for lead-acid and Ni-Cd batteries. Telecom facilities also get a exemption for lead-acid and Ni-cad installations below 60 VDC. UPS lead-acid and Ni-Cd installations listed to UL 1778 also get a exemption, but other installations will need to comply.

In Section 4.6.4, a provision to gain exemption is provided as the standard permits approval of groups larger than 50kWh or spacing smaller than 3 ft, if large-scale fire testing has been completed and the results accepted by the AHJ.

The general requirements in section 4.8 also place a limit on the Maximum Stored Energy (MSE) allowed in a controlled area based on technology. Installations in most locations other than regulated electric utilities will need to be compliant with the standard.

- Unlimited for Lead-acid and Nickel battery technologies, that includes nickel-cadmium (Ni-Cad), nickel-metal hydride (Ni-MH), and nickel-zinc (Ni-Zn)
- 600kWh for Lithium-Ion, Sodium Nickel Chloride, and Flow batteries.
- 200kWh for any technologies not specially listed.

In Section 4.8.1, the standard permits approval of groups larger than MSE, based on a hazard mitigation analysis and if large-scale fire testing results are done and accepted by the AHJ.

In all cases, a careful review of the standards by both manufacturer, installers, and end-users will need to be completed whenever a product is installed above the limits to verify there will be no surprises when it comes time to get permits for construction or occupancy. The exemptions are very specific so even some telecom and utility customers are subject to compliance depending on the location where the energy storage is placed, and the intended application (e.g., traditional stationary standby vs. grid-interactive).

Technology specific requirements

The NFPA 855 standard has technology-specific requirements for electrochemical storage systems in Chapter 9 and is broken out in table 9.2. These apply above and beyond the general requirements and will be different based on electro-chemical technology.

They are specifically addressed in the table as follows:

- Lead-Acid – all types
- Nickel - includes nickel-cadmium (Ni-Cad), nickel-metal hydride (Ni-MH), and nickel zinc (Ni-Zn)
- Lithium-Ion – all types
- Flow
- Sodium Nickel Chloride
- All Other Electro-chemical ESS and battery technologies

The specific requirements for the above-mentioned technologies in this table are based on the following seven compliances:

- Exhaust ventilation
- Spill control
- Neutralization
- Safety caps
- Thermal runaway protection
- Explosion Control
- Size and separation

Each technology has requirements based on these seven compliances indicated by a simple YES or NO in each category.

For Sodium Nickel Chloride Batteries, Exhaust ventilation, Spill control, Neutralization and, Safety caps are marked as not required (No). Thermal runaway protection, Explosion control and, Size and separation are marked as required (Yes).

Most of the applications where Sodium Nickel Chloride Batteries are deployed fall under the applicability of this standard and based on the behavior of the technology in operation, it was rated inaccurately against these compliances, so action was needed.

Challenge presented, what was done

When the NFPA 855 standard was proposed it was immediately noticed that the Sodium Nickel Chloride battery technology was not specifically addressed. This created concern that drove their participation in the development of the standard. Their goal was to have the technology understood and validated with any required testing before the adoption of the standard became widespread. To help the committee gain an understanding of the technology, public input and comment to the standard draft were done and presentation of the Sodium Nickel Chloride Battery technology in detail to the technical committee responsible for drafting the standard was also completed. Before the standard was released, the committee agreed to add the technology to the list in Table 9.2 with limits that were in line with other alternative technologies that the standard seemed to be targeting. However, even with these gains, manufacturers were still required to comply with areas that were inaccurately aligned with sodium nickel chloride technology.

The work performed with the committee on the draft made it clear the market would be affected by this standard. The decision was made to be ready before the adoption of the standard by having the required listing and test data needed to present to the AHJs for review.

Sodium Nickel Chloride Battery listing and testing requirements

Based on their interpretation of the NFPA standard and the way the sodium nickel chloride battery is deployed by their markets, listing to UL 1973 and large-scale fire testing to UL9540A would be required to gain exemptions to the requirements. This would allow their customers to take advantage of the safety and energy density as well as other benefits of the technology. Since the product had already been listed to UL 1973, this was not a new requirement for us as a manufacturer, but for other companies and technologies, this may or may not be true.

The large-scale fire testing to UL 9540A is a new requirement for all technologies. The UL9540A test method is used to gain NRTL reports with data that an AHJ can use to determine the risk of an energy storage system and highlights requirements that mitigate the risks of conflagration to adjacent systems or parts of the building.

The UL 9540A is a detailed test and data collection method for large-scale fire testing of battery systems and Energy Storage Systems that include batteries. This test method is mainly centered on thermal runaway being the trigger to fire conflagration hazards but extends beyond that into other possible failure modes that could cause fire or release of dangerous materials. These additional modes include mechanical and electrical abuse. The standard has requirements to begin testing at the Cell level, moving to the Module Level, Unit level, and finally the Installation level if required.

The fourth edition (dated November 12, 2019) has clear paths for a manufacturer seeking testing to follow. The sequence includes the information that is reported and any performance criteria required to discontinue testing at that level.

These can be summarized at each level as follows:
Cell Level Test

- Reported information
  - Cell design
  - Thermal runaway methodology
  - Cell surface temperature at gas venting
  - Cell surface temperature at thermal runaway
  - Gas composition, LFL (Lower Flammability Limit), Burning velocity and, P_{max} (Maximum Pressure)
- Performance criteria so no further testing is required
  - Thermal runaway cannot be induced in the cell
  - Cell vent gas is nonflammable in air in accordance with ASTM E918

Module Level Test

- Reported information
  - Module Design
  - Heat release rate
  - Gas generation and composition
  - External flaming and flying debris hazards
- Performance criteria so no further testing is required
  - The effects of thermal runaway are contained by the module design
  - Cell vent gas (based on the cell level test) is nonflammable

Unit Level Test

- Report Information
  - BESS design
  - Heat release rate
  - Gas generation and composition
  - Deflagration and flying debris hazards
  - Target BESS and wall surface temperature
  - Heat flux at target walls, BESS, and means of egress
  - Reignition
- Performance criteria so no further testing is required
  - Target BESS temperature less than cell surface temperature at gas venting measure in cell level test and meets heat flux limits for means of egress
  - Temperature increase of target walls is less than 97° C (175° F)
  - No explosion hazards exhibited by the product
  - No flaming beyond outer dimensions of the BESS unit (for indoor, wall-mounted unit)

Installation Level Test

- Report information
  - Fire protection equipment
  - Target BESS and wall surface temperatures
  - Gas generation and composition
  - Deflagration and flying debris hazards
  - Heat flux at target walls
  - Reignition
- Performance criteria
  - Target BESS temperature less than cell surface temperature at gas venting measure in cell level test
  - Temperature increase of target walls is less than 97° C (175° F)
  - The flame indicator shall not propagate flames beyond the width of the initiating BESS
  - No flaming outside the test room and meets heat flux limits for means of egress

The scale of the testing increases as the test levels progress. Therefore, achieving results that allow the manufacturer to stop at the lowest level possible is desired.

UL 9540A testing of Sodium Nickel Chloride Batteries

Figure 1 shows the Sodium nickel chloride product in the form it would be tested for all levels described in the test method. To test the unit at the installation level would have been extremely cost-prohibitive so the goal was module level as the stop point. Testing of the Sodium Nickel Chloride batteries was done at the cell level with acceptable results. Testing at the module level was also done so there was no confusion with the AHJ on what was tested. The cell is not visible for examination when installed, therefore an AHJ or inspector would not be able to see it to verify that what was tested is what is installed. The module level testing also corresponds to the level where the UL 1973 listing is done. The manufacturer felt this would be the best way to obtain acceptable data to present to the AHJ to gain the exemptions (or modifications to the rules) that their markets require.

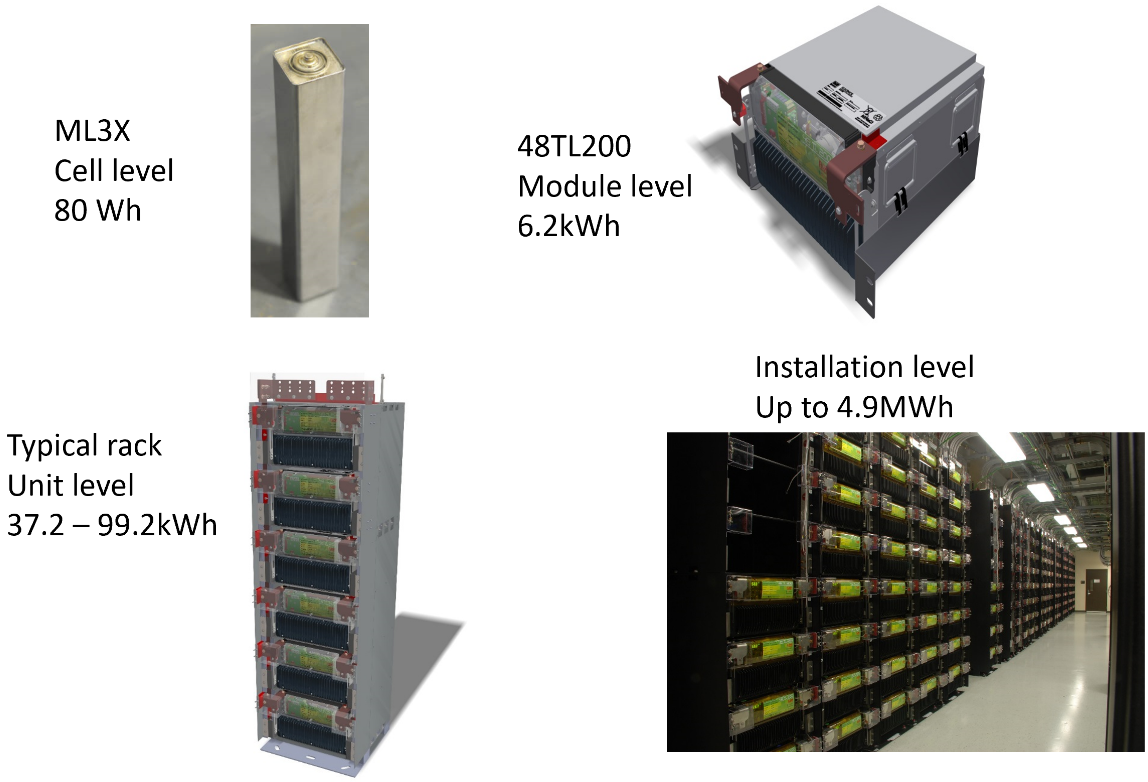

Figure 1. Potential test levels of sodium nickel chloride technology UL 9540A testing of Sodium Nickel Chloride Cells

Cell level testing is done at the smallest level of energy storage used in any technology. In some cases, this level is used by the end-user or integrator to build installable systems. Since the Sodium Nickel Chloride cell is not designed to be used without the support of a module design and enclosure, the typical cell use case was modified to allow testing to be accomplished at this level. In other words, it was tested outside of the way it is typically used in deployment for the purpose of obtaining data.

After technical discussion with UL's test and fire engineers on the design of the technology, tests were developed and planned to comply with the test method as is typical for any technology.

Testing of the Sodium Nickel Chloride cell level was conducted on 10 cells to achieve results per the standard. The test consisted of five different methodologies to potentially induce thermal runaway, explosion, or release of dangerous or flammable gases. The five methodologies are as follows:

- Overcharge
- External short circuit
- Nail penetration thru outer cell case
- Nail penetration thru outer cell case and separator
- Overheating to >800° C

In all cases, the cells were tested at 100% SOC and at the internal operating temperature of 265°C. As stated above, the cell cannot be used in the manner tested, so specialized test apparatus was developed by their team to heat and maintain the cell at operating temperature. The cells selected for testing could then be removed from this temporary container and the test performed on just the cell itself.

UL 9540A Test Results for FZSoNick

Cell Level Test →

Cell design: FZSoNick ML3X, sodium nickel chloride chemistry, 38 Ah, 2.6 V, 695 g (1.5 lbs)
Thermal runaway methodology: External short circuit resulted in self-heating; overcharge, nail penetration, and overheating were also demonstrated
Cell surface temperature at gas venting: 780°C (1436 °F) determined through overheating test
Cell surface temperature at thermal runaway: N/A – Thermal runaway not induced by overheating cell
Gas volume: Less than 0.5 L
Gas composition: 9.6% CO, 22.4% CO2, 63.9% H2, 4% hydrocarbons
Lower Flammability Limit: Testing not conducted.
P_{max}: Testing not conducted.
S_u (Burning Velocity): Testing not conducted.

Figure 2. Cell level test results of sodium nickel chloride technology.

The test results were discussed with the UL team after completion, and there was some discrepancy on the results from the manufacturer's perspective and technical knowledge of the chemistry. There is no dispute on the gases or quantities that were measured, the manufacturer does, however, question where they came from. The cell does not contain the materials that would produce the gases measured, and given the relatively small amount of gas measured, the only realistic interpretation is that the materials that produced the gases came from the test apparatus, test leads, tapes, and materials used to temporarily secure them for the test cycle.

In all cases, the testing was unable to induce thermal runaway. The mechanical damage and overheating tests produced the most dramatic results with the cell case splitting in the worst case. Though this test did prove you can push a sodium nickel chloride cell to failure, it was not a thermal runaway event. The cell failed because of internal over-pressurization. The report points to the material vaporization of the salt electrolyte as the source of the expansion.

From the manufacturer's perspective, and with their understanding of the physical properties of the product, they don't think that was accurate because of the following supporting arguments:

- While the materials in question can change phase (boil) at approximately 780° C, that reference is at sea-level pressures. The cell in operation has higher internal pressures than sea level, which increases the vapor pressure temperature of the material proportionally.
- The materials in question are inside the nonmalleable ceramic separator, so the vaporization of these materials would not cause the outer case to swell without first causing the ceramic separator to break. Separator failure would cause the active materials to react with each other producing stable solids, table salt (NaCl), and aluminum (Al), at known temperatures <680°C, well below the level the test was being conducted at. This would have prevented any further expansion internal to the cell because the material reduces in volume when the phase change from liquid to solid occurs.
- The data supports the conclusion that since the cell charge efficiency increases with temperature, the testing at the elevated temperature caused the production of more of the active ingredient responsible for the state of charge (metallic sodium). This material has a vapor pressure temperature of 886°C at sea level, so a phase change from a solid to a gas is not possible. The failure resulted from the increase in material that produces an increase in internal pressure. This places equal force on the seamed metallic cell case and the seamless ceramic separator. The seam is the weakest mechanical link when it is not contained so it eventually fails before the ceramic. In the module design, this expansion is not possible because of mechanical containment, therefore the pressure increase will fracture the ceramic before the cell case can expand and in effect neutralize the active ingredients as described above.

They were able to offer this explanation to the report authors and they did place a small notation in the report that informs the reader that the cell would be unlikely to expand in this fashion based on module design. They would have preferred the report to contain a more technical explanation, as in most cases the reader will most likely look for the worst-case results in the report regardless of whether they apply to the real-world application.

Based on the test method, the Sodium nickel chloride cell meets the performance criteria, so no further testing was required. However, with the modifications that were done to put the cell in an active state, and since they were able to push the cell to failure during testing for reasons stated above, they felt the AHJ would have a difficult time determining the true safety risk of the technology. Therefore, a conscious decision was made to move on to the module level testing to provide more detailed results for a real-world scenario.

UL 9540A testing of Sodium Nickel Chloride Modules

Module level testing is done at the subassembly level of energy storage for any technology. The subassembly is used to build larger BESS systems. The module tested is as shown in Figure 1. The results of the testing are shown below in Figure 3.

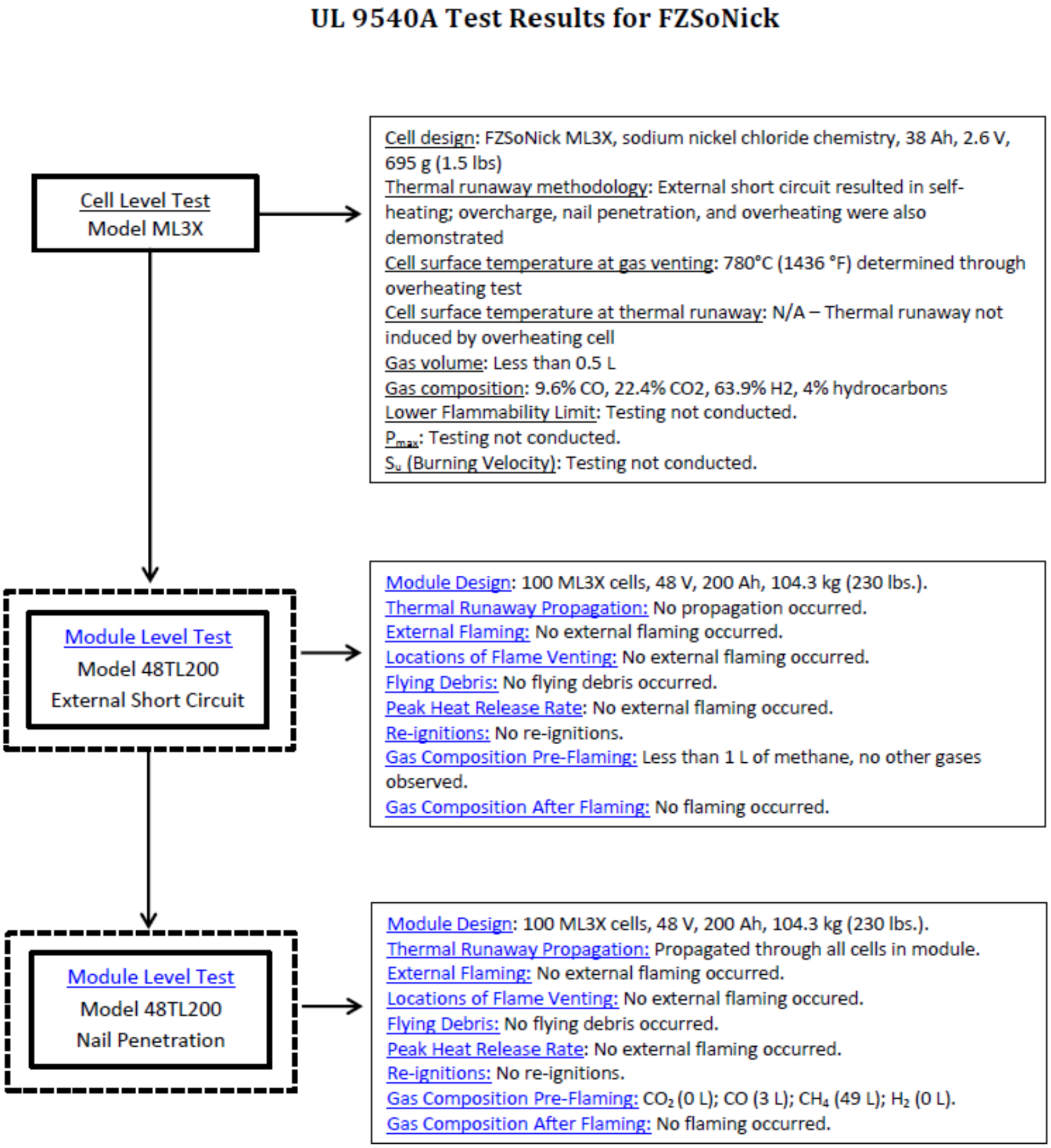

Figure 3. Module level test results of sodium nickel chloride technology.

Testing the Sodium Nickel Chloride Module level was conducted by performing two separate tests on a single test sample to achieve results per the standard.
The test consisted of two different methodologies to potentially induce thermal runaway, explosion, or cause a release of dangerous or flammable gases.
The two methodologies are as follows,

- Short circuit of primary and secondary cell
- Nail penetration thru outer and inner enclosure, penetrating thru one and one half cells

In both cases, the module tested was conditioned (cycled multiple times), fully charged, and at nominal internal operating temperature (265°C). (Note that due to insulation, the external temperature of the module is only a few degrees above ambient, so that users are never exposed to the high internal temperatures.)

Similar to the cell tests, the internals of the module needed to be modified and instrumented with various test leads and conductors to initiate the short circuit fault. Modifications to the external case and insulation system to provide exit holes for the wiring and cabling were made. This modification would be equivalent to relatively severe mechanical damage. In all real-world cases, this type of damage would warrant a firm recommendation to remove the module from service. The modifications were all well documented in the report and are shown in Figure 4. The rear of the case was also modified by drilling a $^{3}/_{16}$” hole to facilitate the nail penetration test.

Figure 4. Sodium nickel chloride Module level test unit with instrumentation modification

The outside of the module was also well instrumented to collect temperature data from all exposed surfaces. The Module was then placed under a smoke collection hood with an oxygen consumption calorimeter. The testing commenced with shorting of the primary cell and then a secondary cell in the center of the module while collecting data and observing the behavior. This test did cause the cells that were shorted to fail and cause the internal cell surface temperatures to increase to above the module's maximum operating temperature of 350°C. There was no indication that cell to cell propagation occurred during these tests.

The same module was used in the nail penetration test. The test was conducted less than ten minutes after the first test to minimize energy loss in the unit under test. This test was designed to pierce entirely through one cell and halfway into the adjacent cell as shown in the figure below. The cells marked with an 'X' are the cells that failed in test #1.

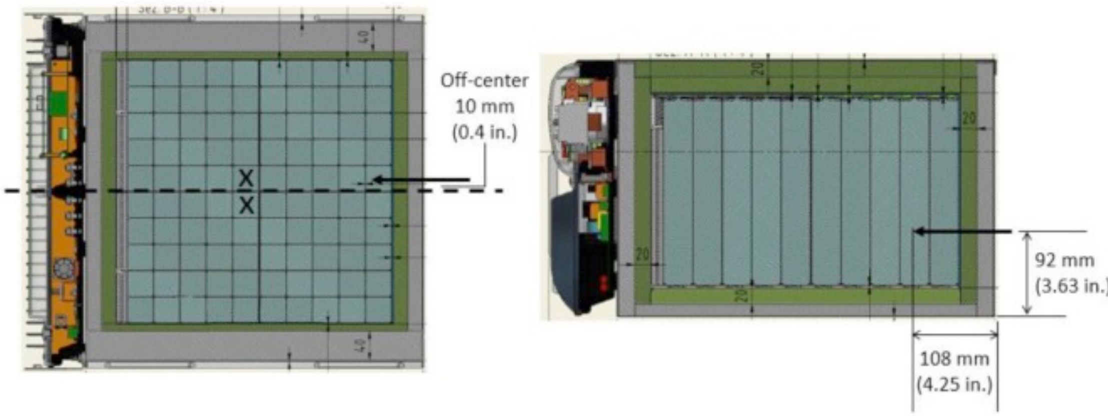

Figure 5. Module level Nail Penetration Test

The behavior of sodium nickel chloride products during nail penetration or other severe mechanical damage testing is well known by the manufacturer. Many similar tests have been done and the results have been previously published. The results of this testing were what they expected. The test results show that the internal surface temperature of the cells that were pierced were elevated and erratic indicating that internal short-circuiting was occurring. The internal short-circuiting was caused by the release of conductive active materials of the initiating cells. This event did propagate to a large portion of the cells in the module. The temperature release of the failure reaction of sodium nickel chloride batteries is known to be approximately 680°C, and this was confirmed by the test data showing the average temperature inside the module was 673°C and had reached this number after approximately 120 minutes. The module design requires a highly insulated container that provides substantial thermal protection to the external environment in the event of internal failures. The external temperature of the module was limited to a maximum of 122°C (252°F) on the unmodified surfaces. The top surface of the module did reach a temperature of 206°C (403°F) but as noted in the report this was most likely due to the modification for test #1 that may have impacted the temperature measurement. During the test, a small plume of gas and particulate was released mainly through the modification in the module's top panel, which is not a feature of the product design so it impacted the test results similarly. At no time during the testing was there any flaming or flying debris observed. The data showed that there was zero heat release rate because there was no external flaming and the only data collected was an artifact of instrumentation noise. The heat flux was also collected, and the instrumentation showed that it never registered above 0 kW/m^2.

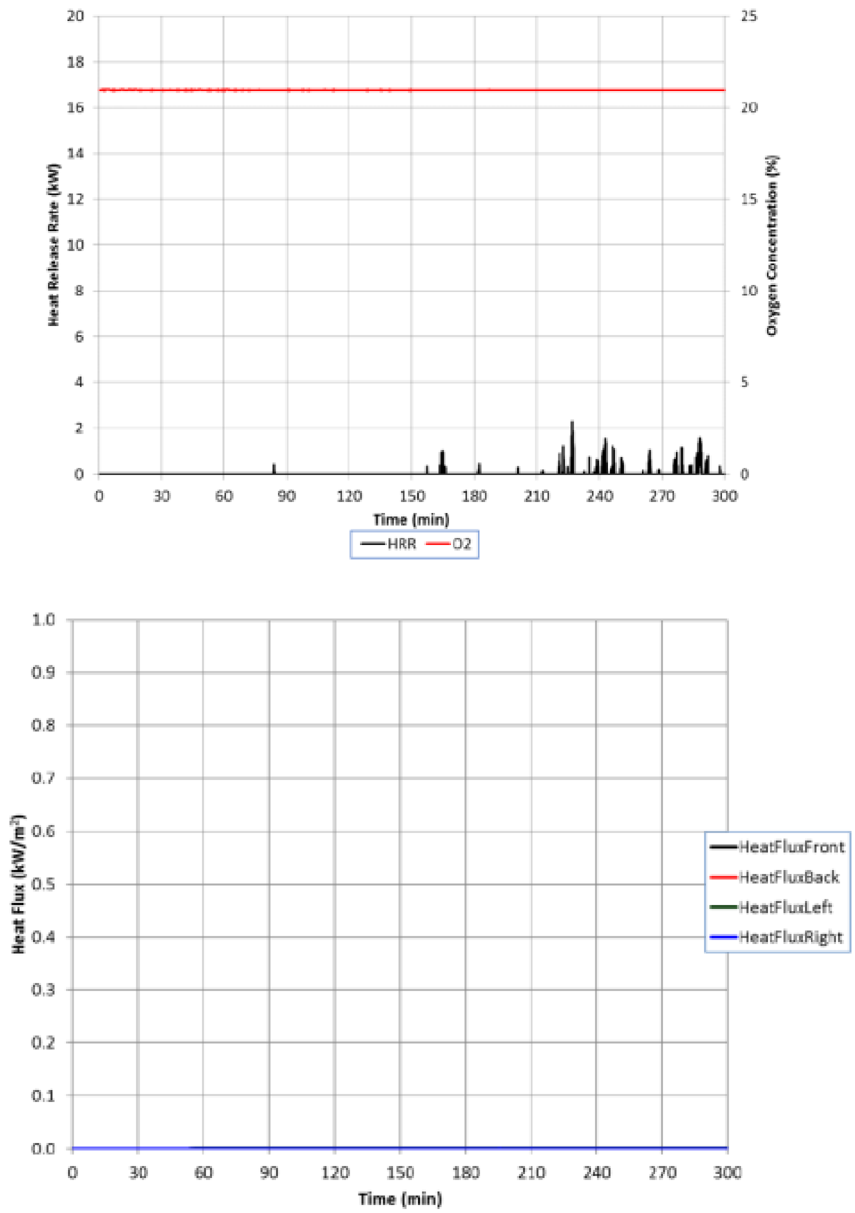

Figure 6. Module level Heat Release and Heat Flux data

As stated above, there was a single regime of off-gassing observed during the test. Flaming ignition of the gases was not observed. The gases were analyzed and identified as traces of methane and carbon monoxide. The peak concentrations of methane and carbon monoxide were 8 ppm and 57 ppm, corresponding to flow rates of 0.01 L/s and 0.1 L/s, respectively. The total measured quantity of methane was 49 L. The total measured quantity of carbon monoxide was 3 L. None of the gases measured above the noise level of the Flame Ionization Detector and zero hydrogen was measured. Just as in the cell tests, they are still looking for an explanation of the source of the methane. While the volume and release rate is very small, it has, in some cases, forced us to calculate the ventilation for keeping this below 25% of the LFL on request by an AHJ. It should also be noted that upon initiation of these tests the battery management system indicated an alarm condition and isolated the module from the external energy source (DC Bus) as designed.

Summary

UL 9540A Cell and Module level testing of Sodium Nickel Chloride batteries in both cases verified the test results performed by the manufacturer previously and have provided us with NRTL reports that they have presented to the customer base and Municipal code enforcement officials when questioned on compliance to the new fire codes.

The challenge remains that there are a very large number of these professionals (41,000+ nationally) and presenting this information on an individual basis is extremely resource-intensive. The lessons they learned from this experience are impacting the way they look at the market, their technology and their testing needs. It also highlights the necessity to continually scan the environment for both intrinsic and extrinsic factors that could cause changes that can affect your technology, market position, and resource needs. One of the most important lessons learned is that the need for proactive participation in the development of the new codes and standards by the manufacturer has become compulsory.

References

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4. A. Klieger, T. Skowera, “UL9540A Module Level Test Report Model 48TL200, Project 4788447606”
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Authors Note

This document was written before and its release was delayed because of the 2020 global pandemic. The standards referenced in this document have evolved in some cases and more current editions may have different levels for requirements. It is the author's recommendation to evaluate the current version of the standard as it applies to specific applications when investigating the challenges this document outlines.