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Li-Ion Battery Pack Immersion Exploratory Investigation

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16. Abstract

This research project was initiated by the National Highway Traffic Safety Administration to assess Li-ion battery pack immersion. Immersion of an electrified vehicle's battery pack is a relatively infrequent occurrence in the real world, especially with a depth of water that can fully immerse a battery pack, yet there are many insights to be gained from exploratory testing of these conditions as they represent an extreme safety scenario for a battery system. With this in mind, while not necessarily an explicit evaluation procedure direction or specification, understanding the safety implications of battery immersion could help provide guidance and background materials to a range of stakeholders including manufacturers, first and second responders, and the general public. Additionally, these events may also highlight or accelerate other issues with a battery's safety system that would not necessarily appear during more routine testing. Moreover, as more electrified vehicles begin to see use on-road, more and more electrified vehicles would be expected to be involved in large-scale flooding events, which may increase the frequency with which immersion occurs in the real world. Therefore, it may be worthwhile to investigate the procedures to be used as well as the response of recent Li-ion batteries under these conditions. Findings and recommendations related to the above noted goals are discussed in the body of this report.

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1 Introduction

Immersion of an electrified vehicle's battery pack is a relatively infrequent occurrence in the real world, especially with a depth of water that can fully immerse a battery pack, yet there are many insights to be gained from exploratory testing of these conditions as they represent an important safety scenario for a battery system. Researching and understanding the safety implications of battery immersion could help provide guidance and background materials to a range of stakeholders including manufacturers, first and second responders, and the general public. Additionally, these events may also highlight or accelerate other issues with a battery's safety system that may not necessarily appear during more routine testing. Moreover, as electrified vehicle become more popular among consumers, the probability of electrified vehicles to be involved in large-scale flooding events also increases, which may increase the frequency with which immersion occurs in the real world. Therefore, it may be worthwhile to investigate the procedures to be utilized as well as the response of recent Li-ion batteries under these conditions.

The project was designed to accomplish the following two goals:

(1) Provide educational materials and background testing for immersion behaviors and results; and

(2) Investigate differences and recommendations across various procedures (and identify any gaps or differences in the procedures).

Findings and recommendations related to these goals are discussed in the body of this report.

1.1 Highlighted Battery Immersion References and Applicable Insights for Further Investigation

Because battery immersion testing is a key component of many battery abuse and safety evaluation procedures, there are existing battery immersion safety standards, which are used as a starting point for discussion, as well as for leading the exploratory research for the battery pack immersion testing discussed later in this report. During the investigating of the current options for battery immersion testing, differences can be observed for the various testing standards in three primary areas: (1) the salinity of water used for immersion, (2) the duration of immersion, and (3) the post-immersion observation time (if any exists). Three key evaluation methods are summarized below, with underlining to emphasize key parameters and methods in each method.

- **SAE J2464 NOV2009 – 4.3.5 Immersion Test (Module or Pack Level)**
  "With the DUT in its normal operating orientation and at full state of charge, immerse the DUT in ambient temperature salt water (5% by weight NaCl in H2O) for a minimum of 2 hours or until any visible reactions have stopped …." (SAE International, n.d.)

- **USABC Battery Abuse Testing – 4.4 Water Immersion**
  "Salt water should be an approximation of seawater (3.5% (600 mM, 35 ppt) sodium chloride)…. The DUT should remain immersed for (1) a minimum of 2 hours or (2) until failure of the DUT (HSL ≥5)…. DUT should be monitored for at least 30 minutes after the completion of the test." (Orendorff et al., 2017)

- **ISO 6469-1:2019 – 6.4.2 Immersion into Water**
  "Immerse the DUT in ambient temperature salt water (3.5-5% by weight) for 2 hours" + 2 hours post-immersion observation time. Requirements: No fire, no explosion."
  (International Organization for Standardization, 2019)

From this brief summary, several differences for immersion test execution can already be observed. First, the actual salinity of the water used to emulate seawater varies from 3.5% to 5% by weight. Generally speaking, higher salinity levels will lead to faster decomposition and reactions while the battery is under water and thus the discharging of the battery will happen more rapidly, and the test (from a "during-immersion" perspective) is more aggressive in terms of a battery's ability to survive the rapid discharge. In contrast, lower salinity levels and the subsequent slower reactions will lead to a longer testing time for full decomposition or will likely result in a higher state-of-charge when the battery is removed from the immersion for observation, a second step in two of the three examples discussed above. This higher state-of-charge and reduced amount of decomposition prior to observation outside of the immersion leads to a more aggressive evaluation in terms of other factors (such as internal and external shorts within the battery and its related components). Expanding the salinity discussion further, vehicles are sometime flooded in brackish water, which has an even lower salinity level and thus may be worth considering as a supplementary testing point during any testing programs since it further emphasizes the response of the battery post-flooding, which would be a more relevant assessment for items related to stranded energy, and first/second responder best-practices (i.e., likelihood of incident following removal and draining of a flooded vehicle).

The second important difference between the three sample immersion procedures discussed above is the duration of immersion for the test. In the J2464 procedure, the battery is held in the immersion "for a minimum of 2 hours or until any visible reactions have stopped." In contrast, the ISO6469 procedure holds the battery in the immersion for 2 hours and then moves toward the observation stage. The USABC procedure suggests a minimum testing time of 2 hours, but also allows for testing to end if a safety-related failure is observed. The maximum time for the immersion is not directly specified in the USABC procedure, but it is likely that a battery would be removed near the 2-hour minimum specified testing time unless reactions were still occurring (which is somewhat unlikely). Ultimately, the longer the test procedure specifies that battery stay in the immersion (i.e., until visible reactions stop) focuses the test toward a battery's safety behavior during the immersion, looking for safety-adverse reactions such as arcing, venting or any visible flames when the battery is held underwater. In contrast, a shorter immersion duration, removing the battery before all reactions have stopped, will allow for the test to also consider the post-immersion behavior of a battery during the specified post-immersion observation period. As will be discussed in the next section, post-immersion behavior may be an important facet of flooded battery safety behavior for more recent batteries as battery degradation and some incidents have been observed to occur following the removal of an electrified vehicle from the flood condition. With this in mind, immersion test procedures should balance an assessment of safety during and post-immersion with the duration of immersion playing a key role in determining the state of the battery during post-immersion assessment. Specifically, a fully deteriorated battery (where reactions have completely finished) is likely to have a much more muted response, if any, to any issues following removal and draining of the water. Although one may then assume that a shorter immersion time is preferred, a reasonable immersion duration from real-world experiences is not clear since too short of an immersion time may be unrealistically aggressive as a test condition as well. While out of scope for this assessment, the actual duration and degree of flooding for a range of vehicle scenarios is of great importance to better understanding the desired duration of an immersion test.

The third major difference across the example immersion procedures discussed above is related to post-immersion observation. Two of the three procedures mention a post-immersion observation time as part of the test procedure, yet the suggested observation time varies significantly (30 minutes versus 2 hours) and the SAE procedure does not appear to mention a significant post-observation stage to the test procedure, which stands to reason given the focus on full decomposition evidenced via no observable reactions. Focusing on the two tests that do include an observation period, there is a significant departure in the duration of observation for any reactions or events post-immersion. As with the discussion in the section above, a longer post-immersion observation period suggests more emphasis and assessment on any issues that may occur after the vehicle is removed from the flooding, a highly relevant condition for a range of stakeholders and scenarios. Moreover, other vehicle incident data and observations have suggested that incidents may occur on the order of hours or weeks after the initial incident (Smith, 2012). While weeks of observation is likely out of scope for many assessment procedures, the duration of observation post-immersion is still likely an important parameter for immersion testing.

To summarize the discussion above, while several battery immersion procedures provide a strong foundation for assessing the safety-related behaviors of vehicle batteries both during and following immersion, several differences do exist adjusting the focus of a particular assessment toward “during immersion” or “post-immersion” safety behaviors. While identifying a recommended immersion and observation duration is out of the scope of this preliminary exploratory work, this testing does seek to understand some of these issues in greater detail.

1.2 Examples and Discussion of In-Field Vehicle Flooding Incidents and Related Incidents

As discussed in the introduction, vehicle immersion is a relatively rare occurrence, yet it is still likely an important area for further study and evaluation since while rare, the occurrence of a thermal incident following vehicle immersion is significant and can actually create a dangerous situation not only for vehicle operators, but also for the first and secondary responders attending to the scene during and after the flood waters have receded. This section is by no means intended to provide an exhaustive overview of all thermal events related to vehicle flooding, rather highlights some relevant issues to help understand incident typologies observed.

1.2.1 Fisker Karma Issues Following Hurricane Sandy Flooding

While now more of a historical example, the flooding related to Fisker vehicles during Hurricane Sandy (2012) is a strong reminder of the importance of assessing immersion response despite its relative rarity of occurrence. Battery management system (BMS) and cell-related battery issues and failures appeared in many Fisker vehicles affected by flooding related to Hurricane Sandy. A range of issues ranging from cell damage to external enclosure damage (from heating) were observed. Anecdotally, batteries that had higher water levels actually had fewer and less severe damage (suggesting more discharge in flood water likely reduced energy levels, thus reducing severity). Interestingly, many BMS modules on the higher row within the pack were still somewhat operational as evidenced by flashing LEDs. Figures 1–3 show the variety and degree of damage observed across many of these packs, varying from water intrusion to clear indicators of high-energy discharge. Many of the damaged packs show significant BMS board and connector degradation while showing no issues with the individual cells. This again suggests that many of these failures are related to system-level loss of isolation as opposed to cell-initiated failure.

Figure 1. Fisker Karma Flooding – water intrusion of the

Figure 2. Fisker Karma Flooding – BMS and internal cabling damage and shorting

Figure 3. Fisker Karma – evidence of actual individual cell damage

1.2.2 Additional Examples and Discussion of Vehicle Flooding-Related Incidents

While it bears repeating that vehicle immersion is a rare and infrequently occurring issue, these incidents do still occur and offer insights into the real-world problems and possible severity these types of incidents may create.

Another incident with a plug-in hybrid electric vehicle (PHEV) in Canada highlights some of the issues and characteristics of a delayed incident related to flooding. While more information on the incident can be found in Jiang (2019), the incident began when a driver used his PHEV to tow a boat out of the water on a boat ramp when the vehicle rolled back down the ramp and into the water. Shortly after being towed from the water, the vehicle burst into flames with the locations of the flames indicating a likely issue with the vehicle's traction battery. Additionally, the PHEV was still attached to the tow truck when flames started shooting from underneath, an increased risk to not only the driver but also first responders. Images from the event are shown in Figure 4.

An analysis of battery incidents from China ("Statistics and Analysis on fire accidents for EVs," 2018) also highlights some additional information relative to battery thermal incidents likely initiated, at least in part, due to flooding. While one could argue that these statistics may not be representative of all regions globally, they certainly provide insights into the frequency and impacts of flooding as the initiation point for a battery thermal event. Specifically, the analysis looked at battery thermal event spanning from February 2011 to June 2018 and found that 4.6 percent of noted battery thermal events were related to flooding. While certainly not the largest percentage, this number still represents an appreciable number of vehicles in a future with widespread electrified vehicle operation. This supports the argument that vehicle immersion should be an area for research and understanding, although not necessarily attached to a specific test or regulatory standard. This analysis also highlights some specific findings related to thermal incidents, one of which is relevant for the discussion and exploratory work contained in this work. Analysis of a July 2016 thermal event related to two electric buses found that there was a thermal event following the flood water receding – again highlighting the importance of assessing the thermal response of a vehicle post-immersion as well as during the actual immersion.

1.3 Desired Research Goals and Outcome

When assessing some of the in-field examples above and in discussions of the key safety procedures and standards related to vehicle battery immersion, there are clearly some key points worth further investigating and evaluating relative to battery immersion behaviors and evaluation procedures. These include the duration of immersion, post-immersion observation requirements, and the salinity level used for testing. These efforts sought to address these identified issues in an exploratory fashion to investigate and highlight the need for additional, more-targeted research in these areas.

2 Testing Overview

To investigate and collect information surrounding the immersion behavior of several recent Li-ion hybrid-electric and battery-electric vehicle batteries, a series of experimental immersion scenarios and procedures were used to consistently and safely evaluate the batteries relative to their safety performance during and after immersion. As the goal of testing was to gain preliminary insights and suggest further research directions for more detailed examinations of issues related to vehicle battery immersion and any subsequent risks (specifically thermal events) during and following the immersion of the battery vehicle, an overview of the process is provided below to enable a better understanding of the basic steps used across all experiments. The following sections provide additional details and rationale for the equipment and procedures chosen for this exploratory research work.

2.1 Test Facility and Equipment

2.1.1 Precautions and Safety Considerations

While not exhaustive, this section covers basic precautions and safety recommendations.

When working on or around high-voltage systems, always follow the appropriate safety precautions. Read and follow the recommended service procedures for high-voltage systems and high-voltage parts for the vehicle/system under test.

Be sure to wear the appropriate personal protective equipment, which includes Class 0 insulated rubber gloves with leather outer gloves. Always inspect the insulated gloves for defects that might prevent the insulating properties, and do not wear them if they are damaged.

2.1.2 Test Equipment and Setup

As discussed in the introduction, the testing in this project aimed at assessing the immersion of batteries during the initial and subsequent immersion as well as behaviors related to initial or long-term reactions following removal of the battery from the immersion conditions. To these ends, the testing equipment use for these experiments needed to provide a safe location for immersion, a means to lower and raise the device-under-test into and out of the immersion, and a means to observe the on-going experiments and monitor for any incidents. An overview of the key equipment is shown in Figure 4. The reader can see the immersion tank, a repurposed dumpster, as well as the lift mechanism to raise and lower the battery into the tank. The lift mechanism was placed on the forks of a fork-lift to provide the starting height from which the battery could be raised or lowered. Care was taken to ensure the lift has sufficient capability for the various batteries examined, as some were over 400kg. The lift could be operated remotely, allowing the battery to be re-lowered quickly and easily should any issue be encountered during observation above the tank. In contrast to a specific observation area, it was decided early on during experimental developments that the battery should be observed directly over the immersion tank, so if an incident was detected, the battery could quickly go back into the immersion, most likely stopping problem. A remote camera fixed to a lift was used as the primary video collection apparatus as it allowed for directly viewing into the immersion tank and during observation, while allowing test operators to stay a safe distance away in case any thermal issues arose during testing.

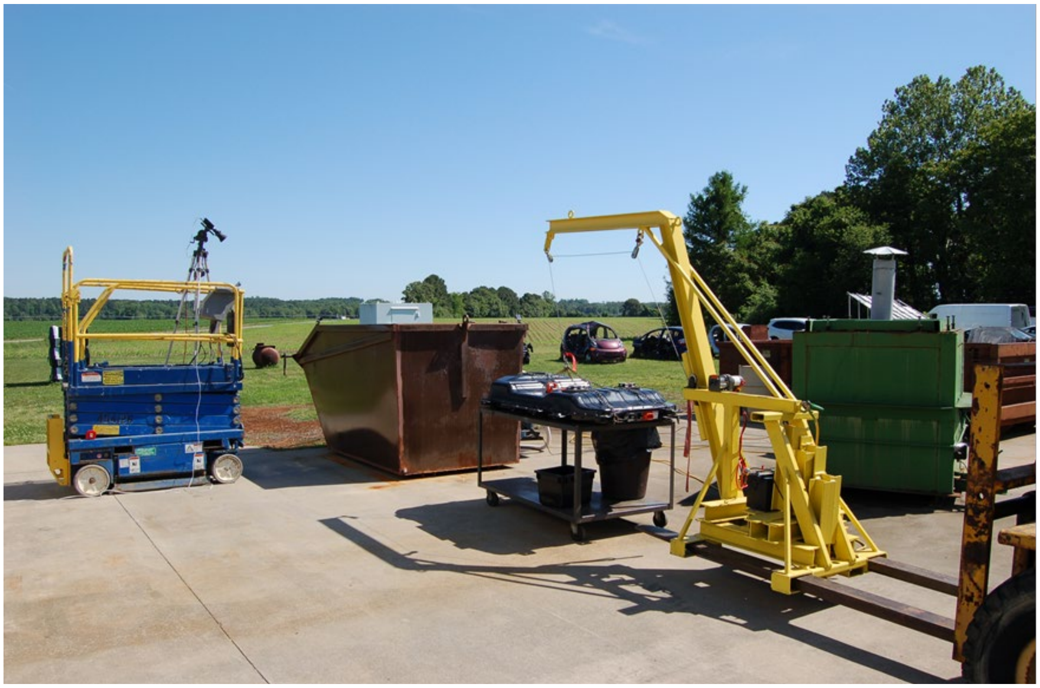

Figure 4. Test setup overview – observation station, lifting mechanism, and immersion tank

The immersion tank for these experiments was a trash dumpster shown below in Figure 5. This provided a robust and cost-effective means to perform the immersion testing and is easily obtainable.

Figure 5. Dumpster used for immersion

As an additional safety precaution, shown in Figure 6, the dumpster was also grounded via welded lugs, large copper wire, and a grounding spike to ensure that the tank was itself grounded to avoid any possible complications during the immersion of the batteries.

Figure 6. Immersion container grounding connections

In discussions with several test engineers and experimental facilities, it was found that immersion tanks quickly become cloudy and hard to observe even prior to the battery entering the tank. With this issue in mind, the immersion tank was retrofitted with a basic pool filtration system to ensure reasonable water conditions prior to the various tests since there was frequently time associated with preparing the batteries and immersion tank that could otherwise lead to undesirable water conditions. This system is illustrated in Figure 7.

Figure 7. "Pool" filter system for immersion water circulation and filtering

As mentioned earlier, the primary camera for the experimental testing was a bird's-eye view remotely provided to a set of displays in the experimental control room. This allowed for safety observation during and post-immersion but was also found to provide the best vantage point during most of the experiments to get an overall feel of testing progress and the emergence of any possible issues during testing. An example of a typical view is shown in Figure 8, where the progress of the immersion (bubbles) can be easily viewed and recorded. Since the remote camera was also recording, the feed also displayed the elapsed time, which was helpful for keeping track of the duration of immersion and observation time as the experiments progressed.

Figure 8. External "bird's-eye" camera view of immersion testing

Supplementing the birds-eye camera was a camera in the corner of the immersion tank near but above the water line of the tank. This camera was particularly helpful identifying the location and initiation of issues such as cell rupture and off-gassing. This camera offered an alternative view during the observation phase that was found to be the location of issues during the experiments as opposed to any issues during the immersion. Figure 9 shows an example view from this camera during a cell rupture event as evidenced by smoke rising from the battery's vents.

Figure 9. Waterline immersion tank camera view

During the initial phase of testing, several additional cameras were used, including high-definition cameras located below the waterline of the immersion setup. While these cameras provided interesting views of the initial submersion while the water was very clear, they ultimately were not found to provide much of an enhancement to the birds-eye camera view. As illustrated in Figure 10, while the initial underwater view (left image) is very clear and shows significant water intrusion as evidenced by the air bubbles emanating from the battery casing, once the immersion and related battery degradation has begun to take place, the water quickly becomes very cloudy and provides minimal visibility. While in some sense, the initial immersion data is somewhat useful to identify any immediate actions, this information can be seen from other angles not requiring underwater cameras to film the immersion. Moreover, the underwater cameras do not provide any information while the battery is held above the tank for observation, which turns out to be where the evidence of an issue was observed for some of the performed experiments.

Figure 10. Underwater camera view during immersion (left - initial immersion, right – approximately eight minutes after immersion)

After the initial immersion and observation experiment was complete for a particular battery pack, the battery was then moved to a secondary location for longer-term observation, final inspection, and final destruction via incineration. The secondary location allowed for additional batteries to be evaluated in the immersion tank while providing a longer-term storage area in case delayed thermal incidents occurred. After the longer observation period, individual batteries were finally incinerated within the enclosure. The secondary enclosure used for this experiment was also a repurposed dumpster, but this time a much larger one to allow for adequate space to retain several packs for observation and examination. The exterior of the containment is shown in Figure 11, and the location of the direct flames used to initiate the final incineration of the battery is shown in Figure 12. Figure 13 shows sample images during and after the battery incineration.

Figure 11. Secondary containment for long-term observation and final battery destruction

Figure 12. Location of direct flames for initiation of battery incineration

Figure 13. Battery destruction

2.2 Immersion Testing Process Overview

The primary goal of this work was to assess the immersion behaviors of select sample batteries. Thus, time was spent to ensure

- reasonable starting conditions for the various batteries;
- safe and consistent immersion protocols;
- observation data while the experiments were taking place; and
- long-term observation following the initial immersion and observation period.

These steps can be divided into four major categories, illustrated in Figure 14 and detailed in the subsections below. The specific steps for this testing are:

- Battery preparation;
- Experimental immersion;
- Removal from immersion and observation above the immersion tank long-term final immersion; and
- Removal and extended observation in secondary container.

For certain experiments, the experimental immersion/observation steps would be repeated if working to assess the impacts of different immersion times with the same battery (i.e., initial short immersion and observation period followed by a longer immersion period). The long-term final immersion was done to ensure the battery was fully de-energized to the greatest extent possible and was typically done for 24+ hours beyond any of the experimental immersion done previously. This helped to ensure the battery was de-energized and thus less active for the final destruction phase of these efforts to collect information during battery incineration.

Figure 14. Overview of battery immersion testing process - Battery preparation, immersion, observation above immersion tank and extended observation

2.2.1 Battery Preparation

As with most battery safety evaluation procedures and best practices, immersion testing should be done at a high state-of-charge, preferably near 100 percent or the expected maximum charge level achieved during normal vehicle charging. Although it is preferred to have the battery brought to the desired SOC using an OEM-supplied vehicle charger and/or in-vehicle prior to pack removal, this is not always feasible or desirable as some test assets may be outside of a vehicle (and were for these experiments) with no diagnostic information available. In these cases, battery voltage was used to confirm the batteries were within an acceptable band of SOC as indicated by their measured voltage compared to known data correlating open-circuit voltage to SOC. To ease the burden for these experiments, a band of 80 to 100 percent SOC was allowable, but the majority of battery packs tested was actually already prepared at a near 100 percent SOC level prior to testing.

2.2.2 Battery Immersion

Parallel with the procedures in the introduction, the batteries were lowered into the immersion tank smoothly and rapidly, allowing the reactions to take place with the battery fully under water and without any major sloshing of the water within the battery. For this testing, the batteries were held at a slight angle (Figure 15) to avoid any air pockets from forming within the battery and possibly floating it to the top of the waterline unexpectedly. This technique appeared to work as all of the batteries remained underwater for the entire duration of their respective immersion tests.

Figure 15. Angled battery prior to immersion (to avoid floating)

2.2.3 Removal From Immersion and Observation Above the Immersion Tank

A key component of these experimental efforts was to observe the batteries directly after they were removed from the immersion tank. From the field examples discussed above, it is hypothesized that this may be the situation that could lead to a possible thermal event and thus precautions were taken to avoid any cascading or escalating thermal events. First, the battery was observed directly above the immersion tank (still full of water). This enabled the battery to be quickly lowered back into the tank if any thermal or related reactions were observed to be initialized. Second, this testing considered any evidence of smoke or cell rupture sufficient to re-immerse the battery. Several of the test procedures mentioned in the introduction do not consider cell rupture and smoke a "failure" condition and continue the observation period until fire or explosion is experienced. Observing the batteries to the point of fire or explosion was deemed out-of-scope for this exploratory testing and thus batteries we re-immersed at the first sign of an issue as opposed to confirming that the initial issue would grow into a larger, and much more serious, thermal event. Ultimately, it is up to the experimenters and/or regulators performing the test to decide what constitutes an acceptable level of thermal incident should the initial phases of one occur during the observation period – this task is left as a topic for further research and consideration outside the scope of this work. Regardless of criteria for re-immersion, the ability to observe the battery outside of the immersion tank following immersion is a key feature of the testing described in this document. Moreover, this ability to "hang" the battery directly over the immersion tank by the lifting mechanism described earlier in this section enables the safe execution of the observation portion of the experiments, allowing the battery to quickly be returned to the immersion if an issue begins to arise. Observation times for this step were on the order of 1–2 hours depending on the desired evaluation scenario.

2.2.4 Removal and Extended Observation Post Immersion

The last step in the immersion procedures used for this testing was to move the battery to a secondary container for long-term observation and ultimately destruction via incineration. As discussed above, this was done in a secondary container equipped with the capability to initiate a fire for destruction of the battery pack. Prior to the final destruction, the battery was held for 24+ hours to see if there were any delayed issues from the previous immersion. At the end of long-term observation, but ahead of the incineration, portions of the battery casing were also removed to observe and document the degree and types of damage to the battery from the earlier immersion. Because the batteries had completed an extended final immersion before moving, the state-of-charge and energy level of the batteries was very low, with all batteries showing less than 50V when tested, suggesting a near-complete de-energization from the immersion.

2.3 Long-Term Observation and Destruction Overview

While not as detailed as the previous discussion, this section seeks to discuss the post-immersion observation and destruction phase of the testing. Following 24+ hours of observation, the battery overall pack voltage was again assessed, this time to ensure sufficient de-energizing from the extended immersion period and the ability to safely examine the pack. The battery covers were then removed to allow for visual inspection of the batteries for the extent of deterioration and damage from the immersion and subsequent removal. Once this stage was complete, the batteries were then incinerated by initiating a fire with an open flame provided by a starter integrated into the secondary container. Once the incineration was initiated externally, the batteries continued to burn until they were nearly completely incinerated. During the incineration, a camera recorded the event. Once destroyed, the batteries were removed from the container to make room for additional test batteries from the immersion. Examples of the process steps are shown in Figure 16.

Figure 16. Overview of final battery destruction process

2.4 Overview of Testing Assets and Conditions

The seven batteries used for testing were provided by NHTSA and represented a mix of BEV and PHEV battery packs from recent testing assets, described in Table 1. While not all batteries were from the most recent model year, the sampling included a mix of modern batteries from a range of manufacturers. This mix of manufacturers was helpful to contribute to the overall exploratory nature of this testing by allowing for a range of chemistries and design topologies to be assessed.

The core of the testing, Batteries 1–5, was done using a 3.5 percent (35 PPT) salinity immersion to emulate seawater and roughly match the conditions of other immersion tests discussed in the introduction. Two additional tests took place in brackish water, which has a lower salinity level compared to sea water. As mentioned, the salinity level at which an immersion test takes place may provide a different immersion and post-immersion response and is very much a topic for further study, as brackish water is broadly defined as anything less than about 35 PPT. For this testing, the two batteries highlighted in blue were tested in a very low 0.1 percent (1 PPT) salinity immersion. This was done in an attempt to roughly match the salinity levels observed and thus conductance of 1,950-2,000 uS[1] for certain types of battery coolant in previous research efforts undertaken by NHTSA (Smith, 2012).

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[1] Microsiemens per centimeter are designated interchangeably as µS/cm or uS/cm, or just uS.

Table 1. Overview of immersion test assets and salinity conditions (no color = seawater at 3.5% salinity and blue = brackish water at 0.1 percent salinity)

Test Asset #	Battery Type Capacity	Key Test Parameters
1	PHEV 8.8 kW-hr	Frequent immersion and observation intervals every 15 minutes
2	BEV 16 kW-hr	30 minute immersion time and 1 hour observation time
3	BEV 30.5 kW-hr	Immersion and observation intervals every 15 minutes for 45 minutes.
4	BEV 32.9 kW-hr	2-hour immersion and 2 hour observation
5	BEV 60 kW-hr	1-hour immersion time + 2 hour observation
6	BEV 60 kW-hr	1-hour immersion time + 2 hour observation 0.1 percent Salinity
7	PHEV 8.9 kW-hr	Short duration initial immersion of 20 minutes prior to first observation period. 0.1 percent Salinity

Specific tests were done with immersion times varying between 15 minutes (with immersion at 30-minute intervals for up to 2 hours) and the full 2-hour immersion time discussed in several of the evaluation procedures mentioned above. Given the exploratory nature of this testing, a more exhaustive study with multiple repeats of the same battery would be recommended to investigate the impact immersion time has upon the severity and probability of a thermal event following immersion. Similarly, the brackish water testing portion of these efforts was intended to examine any major differences between the two test conditions and would again require a much more exhaustive test matrix of salinity levels and batteries. Furthermore, for both of these test situations a more comprehensive review of the expected durations and salinity levels vehicle batteries expect to encounter in the field would be a strong aid to the specifics of this type of testing as means to evaluate real-world safety conditions and scenarios.

Figure 17 shows images of the different batteries prior to immersion to give a relative overview of the different shapes and case designs evaluated in this exploratory testing. Unlike a few other evaluation procedures, batteries were not tested connected to an auxiliary power supply to engage the contactors during immersion as this was deemed out of scope to the larger goal of obtaining immersion ad post-immersion behaviors of the batteries that could possibly lead to a thermal event. Additional instrumentation and data logging was also not added to the batteries in an attempt to maintain “stock” configurations and behaviors to the greatest degree possible and not introduce any additional failure modes beyond the core battery system. As noted, the goal of this testing was to collect observations and examples regarding battery response during and post-immersion as well as to investigate some of the differences related to implementing the specific immersion tests. This testing was not intended to provide a pass/fail examination for each battery system. Establishing a level of performance and associated test procedures would require more testing as well as repeated tests of the same batteries under the same conditions to assess (to some extent) the degree of frequency where an issue may be observed during testing. As discussed, the topic of a "pass/fail" criteria for battery immersion testing is an open research question requiring much more thought and evaluation depending of the specific goals of a particular testing procedure document.

Figure 17. Images of battery test assets prior to immersion (duplicate battery sample only shown once)

3 Test Results and Discussion

This section highlights some of the high-level findings and suggested areas for further study as identified by the immersion testing of the seven battery test assets. Given the exploratory nature of these efforts, the pass/fail status of individual batteries is outside the scope of this testing. Moreover, experimental parameters were changes test-to-test to assess issues related to how long to immerse different batteries during the testing, so battery-to-battery comparisons would not be meaningful. That said, several consistent observations and avenues for further study become apparent across all of the batteries tested.

3.1 Data Collection for Battery Immersion

As discussed above, one of the major focus areas for these efforts was to obtain information, images, and videos of different batteries during immersion. Many stakeholders have very little actual information or experience regarding what happens to Li-ion batteries during immersion and incineration, thus images and information is of high value to a range of stakeholders. To these ends, these efforts document the immersion and observation period behaviors of these batteries through extensive video documentation. Additionally, a wide range of images during and after the experiments were also created to provide insights into the types of damage and degradation experienced during testing. In total, over 450 GB of data were produced for these efforts to better illustrate and educate stakeholders about the behaviors of relatively modern Li-ion battery systems during immersion and incineration.

3.2 Experimental Observations and Discussion

3.2.1 Behaviors During Immersion

For all batteries tested, no issues were observed during the actual immersion phase of testing. While in the past, some batteries have exhibited arcing and even underwater fires while in the immersion, no behaviors of this type were observed for any of the batteries tested. The overall process of immersion for the various batteries followed a very similar series of events. Directly after immersion, remaining air in the pack was released as evidenced by large bubbles escaping the pack from various openings and vents. After this initial release of air bubbles has subsided, battery degradation and electrolysis of the batteries was indicated by smaller bubbles rising to the surface in one-or-two primary locations. Figure 18 shows an example image of a battery during immersion with bubbling clearly visible on the surface. Depending on the size of the battery, the primary reactions during immersion appeared to last between roughly 30 minutes and 1 hour, with larger batteries having a longer reaction duration compared to the smaller batteries tested in this work. While informative, these observed durations should be treated as approximate numbers, since it is not particularly easy to identify when reactions have “stopped” since the appearance of a few small bubbles is somewhat difficult to detect. With these observations and behaviors in mind, the 2-hour immersion time highlighted in the earlier relevant procedure discussion is likely a reasonable testing parameter for most immersion testing scenarios, although a shorter immersion time could possibly provide similar results for most batteries except for those that are very large or where water will have difficulty penetrating. Given no adverse reactions were observed during the immersion itself for any of the test objects, a focus on post-immersion behavior in addition to “during immersion” for a given immersion scenario is strongly suggested (similar to the ISO 6469 post-immersion observation period).

Figure 18. Example image of immersion behavior (bubbling)

3.2.2 Evidence of Significant Water Intrusion

As would likely be expected from batteries experiencing a relatively long period of immersion, all the batteries tested showed significant signs of degradation due to water intrusion across all major components. Despite having their protective cases installed, water was found to easily enter the packs during immersion as the tank selected was sufficiently deep to fully immerse the batteries with a significant amount of water above them. The following figures highlight some of the observed degradation across the various test subjects, which was consistent across the different immersion scenarios. Figure 19 highlights a common set of battery cell and module degradation observed across all of the immersion tests in that a significant amount of battery cell leakage and corrosion can be seen for multiple cells. In addition to the cells themselves, significant corrosion can also be seen for the module enclosure and metal mounting surfaces of the battery.

Figure 19. Evidence of battery cell and module degradation

Figure 20 shows an example view of immersion related degradation across an entire pack. Again, cell and module level degradation can easily be seen, but also connectors and other metallic surfaces contained within the pack are also severely degraded. Recalling the examples of in-field immersion discussed in the introduction, very similar observations can be made regarding the types and level of degradation observed from the immersion scenarios described in these efforts.

Figure 20. Example pack-level view of battery degradation due to immersion

Figure 21 highlights the significant degree of connector degradation observed for two different test cases, highlighting the ability of immersion testing to stress not only the battery cells themselves, but also the connectors within a battery pack, a point which will be discussed later in this report due to observed issues during the observation period of these efforts.

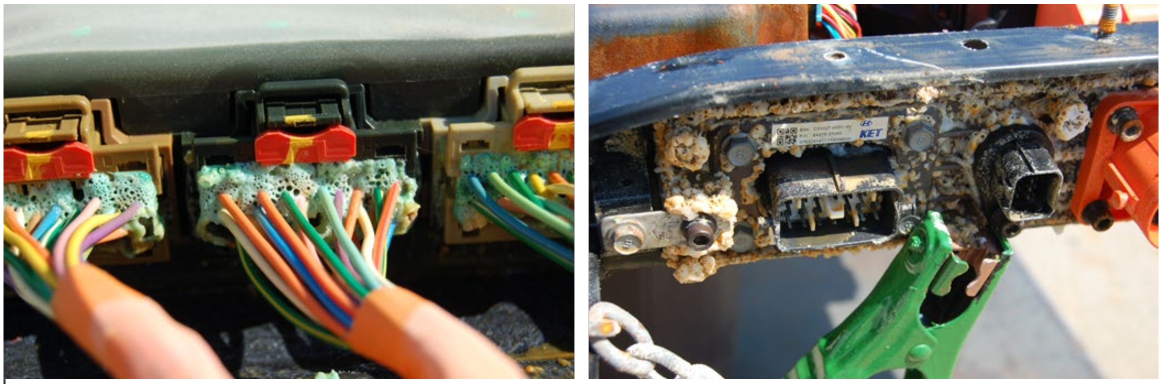

Figure 21. Connector degradation due to immersion

As discussed in the process overview, once the initial immersion testing and observation was complete, batteries remained in the immersion for an extended period with the aim of de-energizing the packs. For every battery tested, this method of de-energizing was successful since all batteries examined post-immersion showed well under 50V, typically on the order of 5V–10V overall. While not necessarily the primary focus of this work, these findings continue to support the generally accepted process of saltwater immersion as a means of de-energizing a battery. Figure 22 highlights this observation, showing a specific pack and voltage-probe result following immersion and before more detailed examination.

Figure 22. Example confirmation of <50V remaining battery voltage following long-term immersion

3.2.3 Preliminary Seawater Versus Brackish Water Observations

As discussed above, one of the study parameters changed for select batteries tested during these efforts was the salinity level of the immersion water – varying between seawater and very low-salinity brackish water. While a study to compare behaviors across varying levels of salinity would be interesting, it was out of scope for this work and thus the efforts are focused on identifying any major differences between the two different salinity levels evaluated. Specifically, only two out of the seven batteries were immersed using the brackish water, so only high-level insights can be gained due to the limited sample size. Fortunately, there were two assets for one of the battery test cases, so at least the same battery configuration could be tested in both water salinity conditions.

For the same battery configuration tested across both salinity levels, the results were relatively similar, but the reactions could be observed to be taking place more slowly in the lower salinity water as would be expected. Figure 23 attempts to illustrate this point, showing an image of both salinity level tests at a point five minutes into the immersion process. The arrows highlight the primary location of bubbling (indicating the degree of reactions) for the two cases. The seawater image shows more vigorous bubbling versus the more muted bubbling observed in the brackish water case. These slower reactions suggest that an immersion test done in brackish water would likely be less aggressive from an initial battery abuse testing standpoint, but might lead to a higher energy state during the observation period, which in turn may be more aggressive from a delayed thermal incident perspective. Ultimately, it is a topic of research relative to the expected salinity as well as immersion time for various battery scenarios, so this work primarily highlights that the expected differences can be observed during testing. Despite the slow reactions for the brackish conditions, in both salinity cases, the majority of reactions appeared to be concluded by the 2-hour immersion time used for these tests, as indicated by little to no observed bubbling.

Figure 23. Battery reactions after 5 minutes of immersion in seawater (left) and brackish water (right)

While a seawater counterpart was not available for the second battery tested in the brackish water, an interesting observation is available for this test as well. Specifically, this battery exhibited smoke/venting during the observation period after an initial immersion of roughly 30 minutes (the shorter immersion time was to investigate any specific issues with short-term immersion in brackish water). This observed issue will be discussed in the following section of this report, but it is interesting that an issue was observed both at the lower salinity level (this example) as well as an additional issue for a different battery at the higher salinity levels. These observations suggest that more research would be helpful to identify if salinity levels play a significant role in the post-immersion behaviors of li-ion batteries.

3.3 Issues Observed Following Removal From Immersion

As discussed above, none of the batteries tested showed any issues during the immersion period. However, two of the batteries tested did show a significant degree of smoke/venting during the observation period and were subsequently put back into the immersion. As discussed above, several batteries were tested with shorter (versus 2-hour) immersion times to see if this lower amount of time in the immersion would lead to any issues during the subsequent observation period. It is expected that removing the battery prior to a full degradation will likely cause a less stable state that could possibly lead to an issue post-immersion but, again, the expected duration of real-world immersion events is outside the scope of this work. Consequently, both batteries with issues observed were removed from the immersion well before the 2-hour test specification. It is not known if these issues would have developed into a larger thermal event or would have just remained in the smoking/venting stage as this was out of the scope of the current efforts.

The first battery that exhibited an issue was removed from the immersion after roughly 20 minutes in the seawater tank. Reactions were still clearly taking place as would be expected from such a short initial immersion. When held above the water, smoke/venting could be easily observed coming from the vehicle, as highlighted in the image shown in Figure 24. After the initial 20-minute immersion and subsequent re-immersion, this battery was again removed from the immersion for observation roughly 15 minutes into the re-immersion to see if any issues would occur following the second immersion. Interestingly, during this second observation period, smoke was again observed suggesting that a longer, 30-minute immersion time could still lead to a possible issue as evidenced by continued smoking. While the volume of smoking was significantly reduced, it was still present, indicating possible issues. As discussed in the introduction, it appears, in this case, that a shortened immersion period may be a possible means to induce an issue in the battery, thus highlighting the value of not only longer-term immersion, but also shorter immersion as a possibly accelerated means to investigate battery failures — subject to real-world judgment related to the duration of possible in-filed events.

Figure 24. BEV (Test #3) battery showing smoke during observation period

A second battery tested during these efforts also showed similar behavior, with observable smoke/venting during the observation period following an initial 15-minute immersion. Interestingly, this battery was tested using a brackish water immersion, thus providing evidence for further study as one battery at each salinity level experience a possible issue and was observed to be smoking following removal from the immersion. Figure 25 shows an image of the observed smoke during the observation period.

Figure 25. PHEV (Test #7) battery showing smoke during observation period

Another interesting observation found during the inspection of the second battery to show an issue during observation (Test #7) was the damage found on specific internal pack connectors and cabling. Recalling the images from the Hurricane Sandy Fisker vehicles (Figure 26), similar degradation can be observed on cabling and connectors for this vehicle. This suggests that in addition to acting as a standardized battery abuse test, immersion and post-immersion observation may also be able to replicate certain conditions found in actual vehicle incidents.

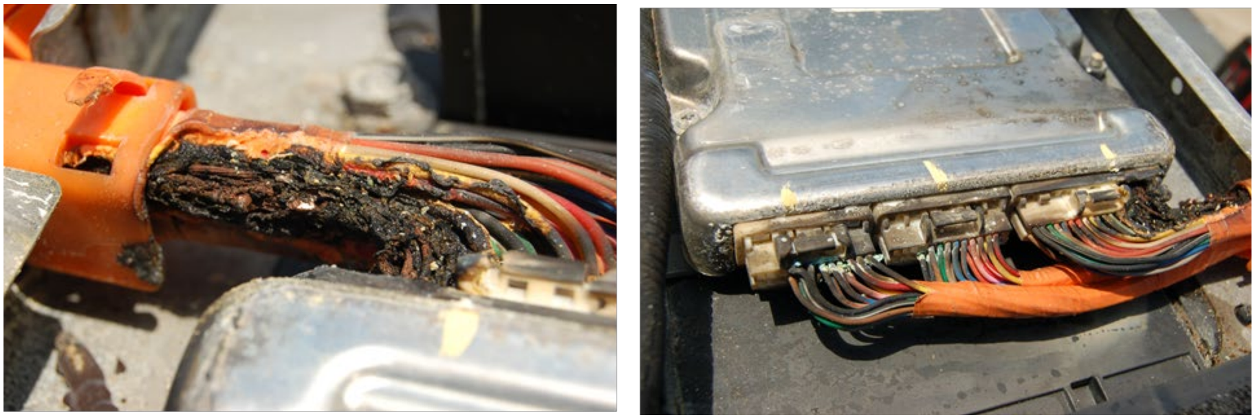

Figure 26. Connector and wiring damage observed for battery Test #7

While the other batteries tested during these efforts did not show any issues during any of the observation periods, observed issues with two out of seven batteries highlight an area for extended research. Additionally, the shorter durations used for the tests that did show a possible issue with shorter-term immersion in both brackish and seawater. As previously mentioned, this work was exploratory in nature, so these results are merely highlighting and validating the importance of a larger study relative to immersion time and possible probability/severity of incidents. Moreover, these pack sensitivities must be compared to reasonable immersion times from real-world incidents to avoid developing too aggressive of an immersion test, unless the aim is to attempt to identify unknow failure modes similar to the observed cabling and connector degradation. Building on this point further, it is possible that not only the battery cells, but also the entire pack can benefit from immersion testing, so one must keep in mind the goals of a particular experiment and not omit the value of system-level testing to identify possible issues at the interfaces or supporting equipment of a particular battery pack. Clearly from these observed incidents a post-immersion observation period following an immersion test is recommended to better assess the performance of a given battery under these relatively rare circumstances.

3.4 Observations During Incineration

In addition to the data and observations taken during and post immersion, the test assets used in this effort were also incinerated following long-term immersion (24+ hours). As with the immersion images and videos, this project sub-component was again done to facilitate the creation of background information and examples of a battery fire in a controlled fashion. To help exemplify this valuable data, Figure 27 shows a time-lapse of the battery incineration for one of the PHEV batteries tested during these efforts. As can be seen in the sequence below, the time-lapse images are useful to understand the progression of the fire from initialization to rather large flames emanating from the pack. It also is useful to provide some basic information related to the duration of the various stages of battery incineration, although these may change significantly depending on the SOC of the battery when incineration is initiated (recall these efforts used nearly fully de-energized batteries for the evaluation and incineration portion of these efforts). Further, despite this battery being de-energized via long term immersion, the video clearly shows significant flames, reminding stakeholders that any battery fire must be approached with caution despite the pack being nearly de-energized. Similar information is available for all seven test objects, with a range of flame levels and durations changing with different battery configurations and sizes.

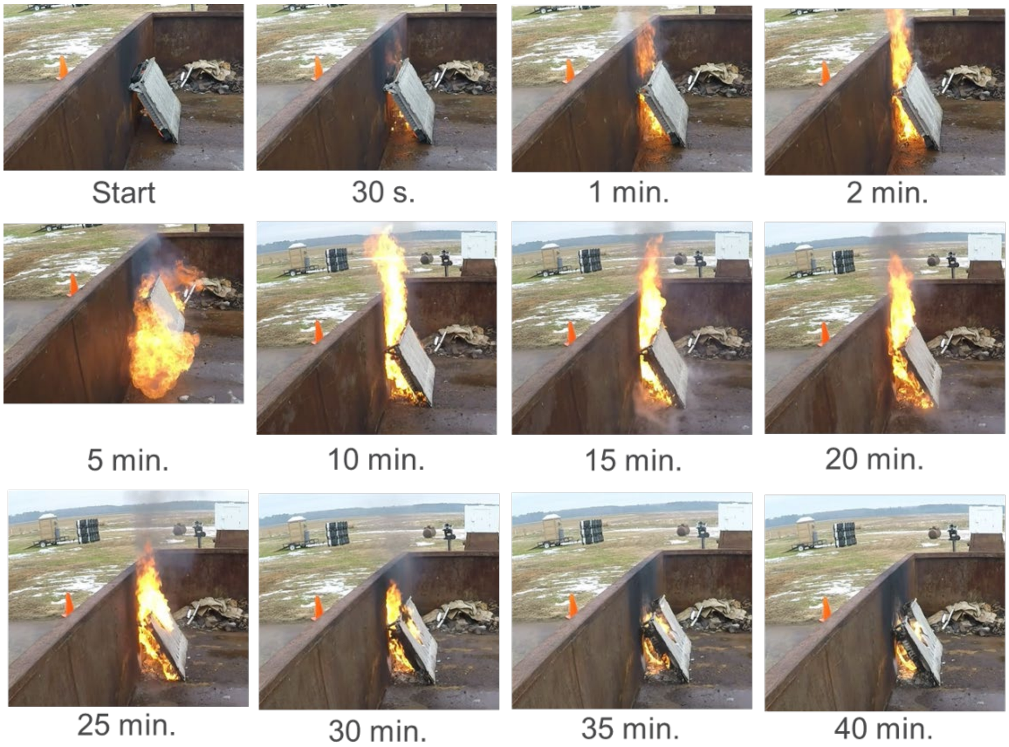
Start
30 s.
1 min.
2 min.
5 min.
10 min.
15 min.
20 min.
25 min.
30 min.
35 min.
40 min.

Figure 27. Example time-lapse of PHEV battery incineration

4 General Conclusions

As discussed above, immersion is a relatively rare, but significant safety scenario for electrified vehicle batteries. While numerous standards and recommended procedures exist for battery immersion testing, they significantly vary across several key characteristics, namely the duration of immersion, post-immersion observation requirements, and the salinity level used for testing. These efforts sought to address these identified issues in an exploratory fashion to investigate and highlight the need for additional, more targeted research in these areas.

In addition to the exploratory goals of these efforts, the current rarity of in-field immersion events also suggests the need for background and example data for battery behaviors during these situations, as they may become more prevalent as overall electrified vehicle penetration increases. In support of this goal, testing performed during these efforts was able to create and provide over 450 GB of high-resolution images and movies during immersion and destruction for stakeholder engagement and education.

Relative to observations made during experimentation, the batteries tested in these efforts did not show any observable issues during immersion (while in the water), suggesting improved immersion performance relative to earlier battery systems that were in some cases known to have thermal issues while in an immersion. Despite this improved immersion performance, several batteries were observed to have a possible issue (as evidenced by smoke/venting) following removal from the immersion. This also aligns with select incidents observed in-field where a thermal incident was initiated after a vehicle had been removed from the water (or the water drained). From these exploratory efforts, it appears that post-immersion observation and safety assessment is a key area for further investigation and research. Specifically, in this testing, two out of seven batteries produced smoke which could possibly highlight the initiation of an issue or be problematic on its own. As mentioned, the goal of this testing was not to observe if the issues grew to a thermal incident, so considerations must be made if smoke alone constitutes an acceptable condition, but this is outside the scope of research.

While not intending to provide a specific procedural recommendation or suggestion, ISO 6469-1:2019 does appear to touch upon most of the items highlighted in these efforts. It contains both a set immersion time as well as a set post-immersion observation time (2 hours in both cases), which is parallel to some of the observations from these efforts. Short immersion times also appear to be an area of interest, although it is unclear how realistic a 15-minute immersion time would be for an actual incident. That said, a shorter immersion time may be a beneficial option to identify any unexpected system-level issues that may otherwise be very difficult to investigate.

5 References

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Appendix A: Applicable Publications

The following publications form a part of this specification to the extent specified. Unless otherwise specified, the latest issue of the publication shall apply.

SAE Publications – Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001. www.sae.org

1. SAE J2464 Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
2. SAE J2929 Electric and Hybrid Vehicle Propulsion Battery System Safety Standard - Lithium-Based Rechargeable Cells

IEC Publications – Available from IEC Central Office; 3, rue de Varembé P.O. Box 131 CH - 1211 Geneva 20 – Switzerland. webstore.iec.ch

IEC 62660-2 Reliability and abuse testing for lithium-ion cells

ISO Publications – Available from ISO Central Secretariat; 1, ch. de la Voie-Creuse CP 56 - CH-1211 Geneva 20, Switzerland. www.iso.org

ISO 6469-1 Electric road vehicles – Safety specifications – Part 1: On-board rechargeable energy storage system (RESS)

UL Publications – Available from UL Corporate Headquarters; 333 Pfingsten Road Northbrook, IL 60062-2096. www.ul.com

UL 2580 Batteries for Use in Electric Vehicles

FMVSS Publications – Available from NHTSA; 1200 New Jersey Avenue, SE. Washington, DC 20590 www.nhtsa.gov

FMVSS 305 Electric Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection

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