Seawater Immersion Testing of xEVs

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Abstract

What happens when hybrid electric and electric automobiles are accidentally submerged in seawater? Conventional vehicles impacted by natural occurances such as hurricanes and floods are usually recycled without the potential for serious hazards. But is this also true for electric and hybrid electric passenger vehicles? Recent testing conducted by TÜV SÜD is yielding data that may contribute to a better understanding of the potential risk of recycling xEVs following immersion in seawater.

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Introduction

Today, manufacturers subject passenger vehicles and their components to rigorous simulation and test regimes that endeavour to make them robust to all known forms of abuse. Some of these test regimes are mandatory requirements, some are recommended practices while others are proprietary manufacturers' tests. An example of mandatory requirements are the National Highway Traffic Safety Administration (NHTSA) Federal Motor Vehicle Safety Standards (FMVSS) standards and regulations. These are minimum safety performance requirements for motor vehicles or items of motor vehicle equipment. As noted in the foreword of the NHTSA list of standards, these requirements are specified in such a manner "that the public is protected against unreasonable risk of crashes occurring as a result of the design, construction, or performance of motor vehicles and is also protected against unreasonable risk of death or injury in the event crashes do occur." An example of non-mandatory recommended practices is SAE International's family of over 10,000 standards. Both of these examples have been built up over many decades of work, beginning in 1911 for SAE and in 1967 for FMVSS.

With the introduction and proliferation of hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) as passenger vehicles (collectively referred to here as xEVs), standards and recommended practices have been added to account for new risks attributed to higher voltage, high electrical power capability and high levels of stored electrical energy. Some examples of these dedicated standards are the proposed FMVSS 141 for minimum sound requirements, and SAE J2929 Electric and Hybrid Vehicle Propulsion Battery System Safety Standard - Lithium-based Rechargeable Cells.

Conventional vehicles have benefited from decades of standards development and accumulated knowledge on how vehicles can be misused, either knowingly or unknowingly. It can be said that we have figured out most of the ways that vehicles can be abused and found ways to make them stand up to this abuse. Accordingly, there are seldom any surprises about how vehicles respond to abuse stimuli, and the outcome is mostly benign except in the worst of crashes. This is primarily the result of robust engineering disciplines used to build safety into all passenger vehicles under all expected circumstances. While this approach works well for conventional vehicles, what happens when the high voltage batteries and power trains are added? Are there new unknown hazards that could present new risks to vehicle occupants and others?

"When compared with the hundred plus years of experience with conventional vehicles, the relatively immature state of xEVs and EV battery development highlights the risks and hazards as yet unknown that will need to be addressed in new or revised standards."

There are several other organisations that have developed abuse test standards in recognition that new hazards may arise from the operation of xEVs over and above those encountered in conventionally powered vehicles. To date, there are about 20 such standards that have been developed and published by SAE, UL, IEC, ISO, the United Nations, the Institute of Electrical and Electronics Engineers (IEEE) and others. But are each of these standards comprehensive in their coverage? Do they account for hazards not only at the cell and battery level but at the vehicle level? When compared with the hundred plus years of experience with conventional vehicles, the relatively immature state of xEVs and EV battery development highlights the risks and hazards as yet unknown that will need to be addressed in new or revised standards.

DOT NHTSA SAE Initiative

Sometimes extraordinary environmental events help to uncover potential vehicle hazards. This was the case when Hurricane Sandy rose over the docks in Port Newark, New Jersey, USA, in late 2012. Hundreds of vehicles were submerged by the ocean seawater. After the seawater had subsided and the vehicles partially dried out, vehicle fires destroyed several of the cars. While it might be assumed that vehicles subjected to seawater flooding would be reduced to scrap value, having them erupt into flame would not be acceptable, especially considering the absence of any obvious warning. One of the most surprising reactions involved a Fisker Karma-brand PHEV that propagated a fire from one vehicle and burned 15 others. The root cause of the fire was traced to a 12 volt fault in an electronic control module mounted on the magnesium steering column. While the high voltage traction batteries were burned in the vehicles, they were not found to be the cause of the fires.

SAE was awarded a contract from the United States Department of Transportation (US DOT) and NHTSA to develop a test procedure for safety performance of lithium ion equipped vehicles. Through both failure mode and effects analyses(FMEAs) and field observations, the high risk areas, including the seawater immersion, were solidified. A small number of organizations were approached to gauge interest and capability to design a test procedure and run indicant validation tests.

TÜV SÜD was selected as the independent 3rd party provider to conduct seawater immersion tests of complete vehicles. The mandate for the program was to develop test procedures with a conductive contaminant using seawater as the source condition and develop instrumentation for measuring isolation loss and state of the high voltage contactors. As well as the test procedures, appropriate safety criteria were also to be developed. Considerations were also to be given for vehicle preparations so that the test would be repeatable. To accomplish these objectives, test data would be instrumental in helping to develop safety standards for seawater immersion if this was determined to be necessary.

The programme started in August 2013 with drafting of the test procedure. Upon completion of the test procedure, building equipment and selecting a suitable test location was addressed. Since the vehicle fires at Port Newark completely destroyed the xEVs involved, it was necessary to use an open test facility that was remote and secured from public access to accommodate the potentially substantial fire size and power that could occur. Two sets of six vehicles were instrumented; one set was tested in late March 2014 and the other set was tested in mid-Summer 2014.

Review of Current Applicable Standards

There are currently standards in place designed to assess the effect of seawater immersion at the pack level.

These are primarily used to assess the leak tightness of the packs. However, it is instructive to examine these standards and determine if there is relevance to the test methods to be developed for a full vehicle seawater immersion.

The standards that were assembled for guidance for this test procedure development are listed in Table 1.

Each one has been examined for relevance to use as part of the test methods development.

It is unusual to find stated rationales for the details of the test method and parameters in these standards. This makes it difficult to apply the lessons behind the development of these standards to the development of new and upgraded standards. Similarly, there is little evidence to indicate whether actual test data was used to set particular values of the standards' parameters. This may be attributable to the ownership of the data by individual companies and the proprietary nature of that data.

TABLE 1: WATER IMMERSION STANDARDS

ID	NAME
SAE J2464	EV and HEV RESS safety and abuse testing
SAE J2929	Safety standard for EV and HEV propulsion battery systems utilising lithium-based rechargeable cells
Sandia 2005 3123	FreedomCAR electrical energy storage system abuse test manual for electric and hybrid electric vehicle applications
UL 2580	Batteries for use in electric vehicles
UL 2271	Batteries for use in LEVs (Light electric vehicle applications)
QC/T 743 201x	Lithium-Ion traction battery
KMVSS 48	Traction battery

Table 2 is a commentary on selected discussion points of the water immersion standards and the corresponding inputs for the R&D tests methods development.

TABLE 2: INPUTS FROM STANDARDS FOR TEST METHOD DEVELOPMENT

DISCUSSION TOPIC	INPUT TO R&D TEST METHOD DEVELOPMENT
Failure Criteria	Not applicable at the R&D level for development of test methods, but will be required for possible standards development. Nevertheless, a set of pass-fail criteria has been proposed
Immersion Solution	The water solution for testing purposes should be standardised for these R&D tests. The average seawater salinity is 3.5% by weight (35g of salts in 965g of water) [1]. The maximum salinity is reported to be in the Middle East oceans, reaching 4.5% [2]. Although some standards call for 5%, for the purposes of these test methods, we will use 3.5% as representative of coastal waters around North America.
Immersion Depth	The standards require full coverage of a device under test (DUT) with water but most of these were developed for packs as DUTs. The DUT in this R&D methods development will be complete vehicles. In order to ensure full immersion or coverage by water, the test specification will be written to the maximum depth of immersion for IP 67 tests as required in ISO 20653:2006 (E). IP 67 depth is defined as 1.0 meter above the lowest point of the DUT. For these tests, the DUT is taken as the battery pack in the vehicle. This will ensure that no matter the position of the pack within the vehicle, it will be completely immersed. This is not an attempt to include water head or pressure as a test parameter.
Test Duration	The referenced standards require from one to two hours of immersion. The system of interest for these tests should include a full vehicle in operating state including system items such as 12 volt components which may not by design be water tight. The duration of the R&D test should be kept as long as practical – in this case, two hours. Note that the criteria for visible reactions at the pack level may not be relevant for this testing since the system level is being tested and the pack is assumed to have already been subjected to water immersion tests as a component in the design verification (DV) process.
Test End Condition	Since the proposed testing will be of a phenomenon discovery nature, test end conditions of 'stoppage of visible gassing' are not applicable to stop these tests. Rather, the objective is to acquire the maximum amount of data. Therefore, continuous monitoring of relevant voltages, temperatures and isolation values will be used to assess when to stop the test. Gassing can still be monitored but not interpreted as the only reason for test termination.

TABLE 2: INPUTS FROM STANDARDS FOR TEST METHOD DEVELOPMENT	
DISCUSSION TOPIC	INPUT TO R&D TEST METHOD DEVELOPMENT
DUT SOC	The existing standards specify either 100% SOC or the maximum %SOC encountered during cycling in service. Thus typical hybrid electric vehicles (HEVs) may only reach 80% SOC, whereas PHEVs and EVs will typically be at 100% SOC. These levels will be used in these R&D test methods according to vehicle platform and manufacturer's maximum recommended %SOC.
DUT Connections Status	The objective of these tests is at the vehicle level including the electric system with battery pack. Accordingly, it makes sense to maintain the complete vehicle electrical system with supporting electrical components in operational state and activated during the tests.
DUT Orientation	The primary purpose of this project is to assess hazards at the system level. Accordingly, the orientation of the DUT will need to be as installed in the application.
DUT	The DUT for these tests will be a vehicle with functioning pack and associated functioning electrical control and thermal management systems.

Test Procedure Development

Safety Considerations

In conducting these tests, it is important to undertake the same care for safe handling of samples and test operation as would be applied to any other hazardous test involving high voltage batteries and elevated voltage electrical bus.

These tests will be undertaken with both high voltage (HV) and low voltage (LV – 12 volts) measurements. At a minimum, HV measurements will be performed by accessing inside the pack enclosure using intrusive and potentially non-reversible changes to the pack. These measures will require extra attention to HV shock risk during the physical intrusion steps, connections and subsequent handling of HV wiring and instrumentation harnesses. Since the pack will be open during this step, all areas of the pack that are not being worked on must be covered by high voltage covers. Some intrusion of the LV bus may be required. Note that, for future tests, the intrusive measures can be avoided if the CANbus data for the HV and LV are available to the test house.

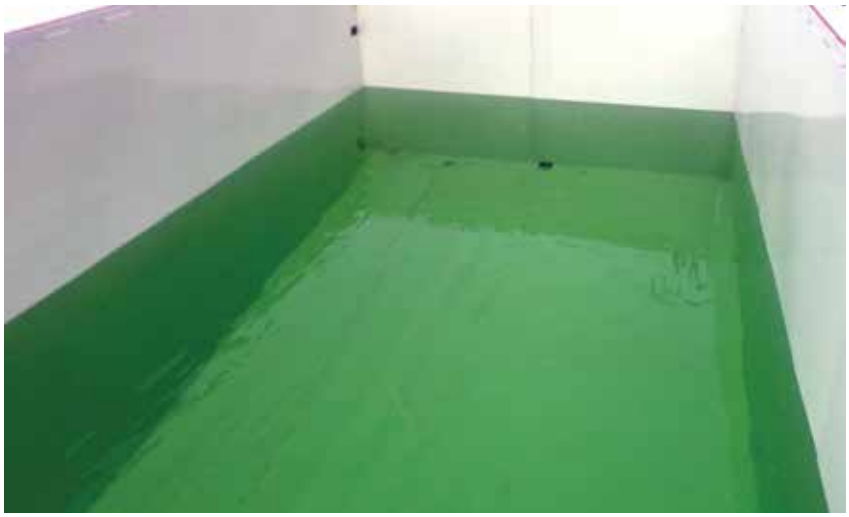


Figure 1: Seawater immersion vessel

It is of paramount importance that test personnel be trained to work with the hazards of the test. This includes:

- Wearing the appropriate personal protective equipment, including Class 0 insulated and regularly inspected and tested rubber gloves with leather outer gloves.
- When working on or around HV systems, always follow the appropriate safety precautions.
- Read and follow the recommended service procedures for HV systems and parts for the vehicle/system under test.
- Ensure that immersion containers, mixing containers and other metallic equipment are well grounded per standard practice and electrical codes.
- Always observe high voltage warning labels.

Test Vehicles

Table 3 summarises the test vehicles, their condition and immersion date. The test sample vehicles were both new and previously crash tested. Vehicle architectures included HEVs, PHEVs and BEVs. Immersion tests were carried out in winter with temperatures well below 0°C and in summer with temperatures above 20°C.

TABLE 3: TEST VEHICLES

VEHICLE	TEST	VEHICLE CONDITION
PHEV 1-1	Winter	New
PHEV 1-2	Summer	New
BEV 3-1	Winter	New
BEV 3-2	Winter	Prior tested - side impact
BEV 3-3	Summer	Prior tested - side impact
HEV 2-1	Winter	Prior tested - side impact
PHEV 2-2	Winter	Prior tested - side impact
PHEV 2-3	Winter	Prior tested - side impact
BEV 2-4u/4l	Summer	Prior tested - front impact
HEV 4-1	Summer	Prior tested - front impact
BEV 5-1	Summer	Prior tested - side impact

Test Immersion Equipment

The tests required the immersion of each vehicle for a two hour period, followed by 28 days of observation. Since the observation period would have made for an excessively long overall test duration, each test was essentially conducted in parallel. The submersion vessels were steel tanks fabricated for the purpose. Each of the six tanks was equipped with a swing door at one end to make insertion and removal of the test vehicles possible without the use of heavy lifting equipment. The immersion phase was conducted in sequence for each two hour period. Seawater was prepared in a separate tank large enough to serve one immersion test by mixing water from a pond supply with salt sourced for the purpose. The solution was agitated to promote homogeneous conductivity. After the test vehicle was inserted into its test submersion vessel, instrumentation was connected. Seawater was then pumped into the vessel in less than 10 minutes. Following the two hour immersion, the seawater was pumped out of the tested vehicle's immersion vessel and transferred into the next vessel for the second vehicle's immersion.

TÜV SÜD engineers prepared each test vehicle with temperature measuring and voltage measuring hardware. The thermocouples were located in several locations in the vehicles to detect any rising temperatures in the battery pack or selected 12 volt components. Voltage sensing lines were connected to the contactors on both sides of the contacts and on the 12 volt signal lines that controlled the contactors.



Figure 2: Gas emissions measurements



Figure 3: Immersion test vessels

Test Results

During the immersion period, some vehicles exhibited unexpected electrical behaviours. Typical events included unintended activation of lights, windshield wipers and horns. These phenomena may have been caused by the closing of switches while submersed in the conductive seawater.

Following the observations period, one of the vehicles, a PHEV, became engulfed in fire. A second vehicle, a BEV, experienced elevated temperatures in the pack. The fire occurred in one of the vehicles in the winter test series, while the elevated pack temperature incident occurred in one of the summer test vehicles.

The PHEV fire event underwent thermal runaway in the battery pack about seven hours after seawater was removed, and the vehicle burned completely shortly thereafter. Other interesting test measurements showed that the HV contactors self-closed about six minutes after immersion phase started. At the 25 minute mark, the pack internal high voltage isolation deteriorated to about zero ohms. Measured temperatures during the fire reached 850°C. The pack had burned internally in almost all zones, but the outer case remained intact but charred.

A post mortem analysis was unable to confirm the root cause of the fire. Another vehicle of this PHEV type was also tested in the summer series and did not undergo any significant thermal event. One identifiable difference in the two PHEV test vehicles, beyond the seasonal influence on seawater conductivity, was the protocol and method used to add the TÜV SÜD instrumentation inside the sealed pack. The first vehicle used TÜV SÜD-developed methods for extracting the pack from the vehicle and for verifying pack sealing performance. The second vehicle used OEM-recommended methods for the same steps. However, a more detailed analysis of the two methods casts doubt on the hypothesis that the procedural differences explain the test outcomes.

The BEV pack temperature rise to a high of 99°C occurred despite using 50% of the salinity in the other samples and a reduction of 50% in the duration of immersion. The pack showed no evidence of internal fire.

Table 4 shows the detailed test performance data from all of the sample vehicles.

TABLE 4: TEST RESULTS					
VEHICLE	TEST SERIES	TIME TO LOSS OF 50% OF HV (MINUTES)	TIME TO LOSS OF 50% OF LV (MINUTES)	TIME TO LOSS OF ISO RESISTANCE TO <500Ω/ VOCSTART (MINUTES)	FAILURE MODE
PHEV 1-1	Winter	430	25	22	Burned
PHEV 1-2	Summer	No loss	46	No loss < target	NA
BEV 3-1	Winter	228	36	21	ISO loss
BEV 3-2	Winter	No loss	No data	No loss < target	NA
BEV 3-3	Summer	103	7	No loss < target	HV loss
HEV 2-1	Winter	9	15	10	Benign
PHEV 2-2	Winter	19	20	19	Benign
PHEV 2-3	Winter	25	25	26	Benign
BEV 2-4u/4l	Summer	65	20	18	99°C then benign
HEV 4-1	Summer	20	17	7	Benign
BEV 5-1	Summer	22	38	21	ISO loss

* Seawater salinity reduced by 50% and immersion duration reduced to 1 hour.

Observations

In the interest of controlling all controllable test variables, the seawater was sampled before and after each immersion event. Analysis of the conductivity showed that the change ranged up to 2.4% in the summer tests, for example, but the change direction was both up and down. Since the conductivity of seawater is twice as high in summer temperatures as in winter, the small changes encountered in test to test were considered as unimportant. Salinity measurements almost mimicked the conductivity changes in direction and magnitude.

Analyses of the major volatile organics changes during each immersion showed decreases in chloroform by up to 30% and increases of 1-2% in toluene and bromofluorobenzene.

The elevated temperatures observed in the BEV pack while measured on the exterior of the battery pack were found to be due to temperature excursions in electronic connectors mounted near the TÜV SÜD pack mounted thermocouples. There was no evidence of related temperature excursions within the pack.

Table 4 is a summary of all data collected for measurements of HV, LV and isolation resistance. The measurement of merit from all of the data suggested that the deterioration of the measured voltages and isolation could be best represented by the time of each to reach a predetermined value. In the cases of HV and LV, this value was set to 50% deterioration. For isolation, the value was set to the commonly used threshold of 500 Ω/volt. Accordingly, the time to 50% loss in HV ranged from as little as nine minutes to as long as 430 minutes for those packs that showed deterioration. Two samples, a PHEV and a BEV, showed zero HV loss and zero isolation degradation over the entire test period of 28 days. One BEV also retained its original isolation value but lost 50% of the pack HV in 103 minutes, indicating a possible internal short circuit. All 12 volt batteries lost 50% of their initial voltage over durations of seven to 46 minutes. With the exception of the two vehicles that either burned or had a temperature excursion, all the other pack and vehicle behaviours were benign, meaning no shock hazard or uncontrolled thermal excursion.

All of the battery packs used in the test vehicles can be described as being either of ‘open’ or ‘sealed’ architecture. Sealed architecture refers to the water tightness of the pack, and in this test programme the sealing performance was tested to the requirements of ISO 20653:2006(E) for IP67 test specification or one meter from the lowest point of the pack. Open architecture describes packs that are clearly not sealed. There may be in-between states of sealing performance but these are likely due to design or manufacturing issues. Of the sealed variety, there were two PHEVs and three BEVs. The remaining open packs were HEVs, PHEVs and BEVs. All open packs suffered rapid voltage deterioration and isolation resistance deterioration in less than one hour. Most sealed packs maintained HV Voc to the end of the test, while only one dropped significantly after one hour. All sealed packs except one maintained the isolation value for weeks.

Summary

The 12 volt batteries all discharged through the seawater and possibly through other loads within one hour. This may be beneficial if the discharge time is very quick to avoid unintended closing of the main contactors and potential shock hazard or risk of a low voltage arc with possible fire. The vehicle that had sealed HV pack architectures performed better if the design objective was to exclude the conductive contaminant from the HV pack interiors. The open architectures however, while allowing the inrush of conductive seawater to access the high voltage components, all succumbed to a 'benign' failure. In the event that either type is immersed in seawater, the open type will likely be unsalvageable, but low risk. The sealed type is more likely to be salvageable but will retain its stranded energy.

This research programme also made recommendations to pursue further investigation into the effect of much shorter immersion durations for open packs, longer immersion durations for sealed packs, and the effects of conducting the same tests using fresh water.

The full description of the test method, results and observations can be found in the NHTSA final report, scheduled to be published in early 2015.

GLOSSARY OF ACRONYMS

BEV – Battery electric vehicle
DOT – Department of Transportation
DUT – Device under test
DV – Design verification
FMEA – Failure mode and effects analysis
FMVSS – Federal motor vehicle safety standards
HEV – Hybrid electric vehicle
NHTSA – National highway traffic safety administration
PHEV – Plug-in hybrid electric vehicle
RESS – Rechargeable energy storage system
SOC – State of Charge

FOOTNOTES

[1] http://oceanplasma.org/documents/chemistry.html
[2] http://www.lenntech.com/composition-seawater.html

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