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Potential Use of Battery Packs from NCAP Tested Vehicles

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Abstract

Several large electric vehicle batteries available to the National Highway Traffic Safety Administration are candidates for use in future safety testing programs. The batteries, from vehicles subjected to NCAP crashworthiness testing, are considered potentially damaged due to the nature of testing their associated vehicles have been subjected to. Criteria for safe shipping to Sandia is discussed, as well as condition the batteries must be in to perform testing work. Also discussed are potential tests that could be performed under a variety of conditions. The ultimate value of potential testing performed on these cells will rest on the level of access available to the battery pack, i.e. external access only, access to the on board monitoring system/CAN port or internal electrical access to the battery. Greater access to the battery than external visual and temperature monitoring would likely require input from the battery manufacturer.

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NOMENCLATURE

DOE	Department of Energy
SNL	Sandia National Laboratories
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
PEV	Plug-In Hybrid Electric Vehicle
PHEV	Plug-In Hybrid Electric Vehicle
xEV	Hybrid, plug-in hybrid and/or electric vehicle
NHTSA	National Highway Traffic Safety Administration
DOT	Department of Transportation
CAN	Controller Area Network
USABC	United States Advanced Battery Consortium
RTD	Resistive Temperature Detector
NCAP	New Car Assessment Program

1. INTRODUCTION

1.1. Objective

This report seeks to evaluate the feasibility of transporting hybrid, plug-in hybrid and electric vehicle batteries (HEV, PEV and EV, respectively) taken from vehicles that have been previously subjected to New Car Assessment Program testing (NCAP) by the National Highway Traffic Safety Administration (NHTSA) to Sandia for future testing programs. The primary areas evaluated are 1) safe shipping requirements, 2) conditions and information required for acceptance of the batteries at Sandia and 3) potential value of any testing that can be performed to NHTSA.

1.2. Background

As hybrid and electric vehicles become more commonplace, it is becoming increasingly important to evaluate the safety performance of their battery systems. While the failures of lithium ion cells have been extensively evaluated, it has most frequently been in the context of single cells intended for portable devices and consumer electronics. These cases are primarily concerned with the impacts of spontaneous field failure and the immediate consequences of a single cell failure.

As hybrid and electric vehicles explore the use of lithium ion batteries new safety concerns have become apparent. It is generally assumed that exposure to abusive conditions for portable electronics devices would be fairly rare. Further, batteries for electric vehicles can consist of several hundred or even several thousand individual cells that may become engaged in an energetic failure even though they were otherwise healthy and undamaged.

Impacting safety as well is the possibility for a cell or battery pack to be damaged as a result of vehicle damage in a way that is not immediately apparent. A Chevrolet Volt in a widely reported incident recently experienced a failure in which a fire originating from the electrical system occurred 3 weeks after standard crash testing. [1] This has led to increased concern of the impacts of vehicular accidents on large battery systems in plug-in hybrid and electric vehicles. Even if cells remain healthy after vehicle damage the stranded energy within the cells may remain an issue. Knowing the state of health of a potentially damaged battery is critical to the safe handling of the cell.

Application of various electrochemical diagnostic techniques may be of use in determining the state of health of a battery pack. A large EV battery pack, however, is a very complicated system and would require refinement of various techniques to determine markers indicative of internal battery damage. Access to large battery packs are necessary to determine what tests will yield useful data as well as be applicable to testing in the field on potentially damaged batteries. This is potentially difficult, however, as large xEV battery systems are not readily available without purchase of a full vehicle.

NHTSA currently has available various electric vehicles that have been subjected to its NCAP testing program. This represents a source of xEV batteries that would be potentially available for testing. However, due to the nature of the NCAP tests the state of the batteries must be

determined before transport to Sandia and subjecting the cells to any testing program. The level of access to the battery system will also affect the potential testing that may be performed. The information available will differ between only being able to read external data, or access to the battery CAN data or even connections to individual cells. This will impact the potential value of any testing that may be performed. This report details these safe shipping requirements, as well as further information required to perform testing. The potential testing that can be done is also addressed, describing the test that could be potentially performed with varying levels of access to the battery pack.

2. SHIPPING AND RECEIVING

This section will address the feasibility and requirements to ship large posttest articles to Sandia National Laboratories. The criteria laid out in this section must be met for large posttest articles shipped to be received by Sandia.

While the battery packs in question would have been originally certified for transportation under UN38.3 their involvement in destructive vehicle testing requires re-verification of the safe transportation of the batteries in question.

2.1 Verification of validity of prior UN38.3 testing

SAE J2950 "Recommended Practices (RP) for Shipping Transport and Handling of Automotive Type Battery System - Lithium Ion" [2] provides criteria for determining the validity of previous UN38.3 certification after use or suspected damage. The following criteria recommended by SAE J2950 are observed, and if any of these are not met the battery is considered damaged. The handling of damaged batteries will be discussed in the next section.

2.1.1. Temperature (J2950 Section 5.1)

Per SAE J2950, the external temperature of the battery pack is measured in a manner that is convenient. The temperature should be at the ambient temperature, and if it is not it should be monitored over time. A battery above ambient temperature should be observed to fall towards ambient temperature and a battery below ambient temperature should not be observed rising above ambient temperature. Once the cell is measured at ambient temperature 3 more readings are taken each separated by at least one hour. If the temperature is seen to rise above ambient temperature the battery is considered damaged.

2.1.2 Explosion[1], disassembly or fire (J2950 Section 5.2)

The battery is inspected visually for signs of explosion, disassembly or fire. If any broken parts are observed or signs of fire such as scorch marks are seen the battery is considered damaged.

2.1.3 Rupture (J2950 Section 5.3)

If any normally internal components are exposed the battery is considered damaged.

2.1.4 Mechanical integrity (J2950 Section 5.4)

Visually inspect the battery pack for signs of lost mechanical integrity, such as broken parts or movement of internal components. If any signs of lost mechanical integrity are present the battery is considered damaged.

[1] This refers to explosion as defined by SAE J2950: "very fast release of energy sufficient to cause pressure waves and/or projectiles that may cause considerable structural and/or bodily damage." However, no explosive material is present within lithium ion batteries and even catastrophic battery decomposition occurs over a much longer timescale than a true explosive material (seconds to minutes vs. milliseconds). Accordingly, batteries cannot be considered truly explosive and even in extreme circumstances would not produce the true characteristics of an explosion.

2.1.5 Leakage (J2950 Section 5.5)

If there are any leaking fluids from the battery pack the battery is considered damaged. Due to the high risk of inadvertent short circuit and other hazards associated with leaking battery fluids, it is highly unlikely that Sandia would accept a leaking battery even if it is properly handled and shipped.

2.1.6 Current interrupt devices (J2950 Section 5.6)

Any current interrupt devices, such as fuses, that are part of the battery system should be inspected and if they have been activated the battery is considered damaged.

2.1.7 Inspect open circuit voltage (J2950 Section 5.7)

The open circuit voltage of the battery should be within its normal operating parameters and not changing significantly over time.

2.1.8 Isolation (J2950 Section 5.8)

The battery system must maintain high voltage to ground isolation of at least 100Ω/V. This can be measured in accordance with ISO 6469-1 or according to manufacturer guidelines. If the isolation is less than 100Ω/V the battery is considered damaged.

2.1.9 Shock (J2950 Section 5.9)

If the battery is confirmed to, or suspected to have suffered a potentially damaging mechanical shock the battery is considered damaged. Due to the nature of the tests the vehicle battery systems have been exposed to they must be considered to have been exposed to potentially damaging mechanical shock. The exception to this would be if a shock sensor is present within the battery system that can verify that the battery has not been exposed to a shock greater than that applied by UN38.3 T4, otherwise batteries from vehicles that have undergone NCAP testing would be assumed under this criteria to have been damaged.

2.1.10 Diagnostic or service tools (J2950 Section 5.10)

Manufacturer's diagnostic tools are used if available to find and resolve any fault codes related to the battery. If any fault codes present a potential safety impact the battery is considered damaged.

2.2 Shipment of batteries considered damaged to Sandia

Batteries that are considered damaged must be approved by an appropriate authority for safe shipping prior to being shipped to Sandia. Two options have been identified for appropriate approval.

The first option would be to have the battery packs recertified according to UN38.3. This would likely require the contracting of a third party to perform UN38.3 T1-T8 testing to recertify these batteries for safe transport.

The second option is to obtain the appropriate permit exemption from the Department of Transportation prior to shipment. Prior discussions with NHTSA have indicated that permits already in place may cover the movement of these battery packs.

Regardless of the method used, shipment of these batteries should be coordinated with Sandia Hazardous Shipping. Further, Sandia is not willing to accept batteries in certain conditions even if they can be shipped safely. This is discussed further in Section 3.

3. ACCEPTANCE CRITERIA

Operational envelopes at Sandia will prevent the acceptance of batteries that are excessively damaged even if it is determined they can be safely shipped. The criteria presented here are used to determine if a cell can be accepted for testing by Sandia. Also detailed are the data available and what further data would be necessary to aid in this determination.

3.1 Sandia Acceptance Criteria

3.1.1 Safe Shipping

All articles received by Sandia must be approved for safe shipping and handling per the criteria presented in Section 2. Any cells, modules or packs received at Sandia that do not follow the appropriate criteria and have the proper approvals may lead to the rejection of future shipments from the same source.

3.2.2 Battery condition

Beyond requirements for safe shipping, articles shipped to Sandia shall be determined to be in good working order. The batteries should be electrically and thermally stable and show no evidence of physical damage. The following guidelines should be observed:

- Store batteries in a safe location for at least 30 days prior to transport to Sandia. During this time no evidence of deterioration or failure should be observed. In particular, significant voltage loss or elevated temperatures indicate the possibility of battery damage.
- Battery must be physically intact. Look for signs of physical damage, such as cracked exterior casing, missing parts or exposed internal parts. Do not transport to Sandia batteries with obvious signs of physical damage.
- Batteries shall be thermally stable. Observe external and internal (if available) temperatures. Temperatures that are persistently above ambient temperature may indicate self-discharge activity within the battery, which over time can lead to thermal runaway.
- Batteries shall be electrically stable. The battery voltage should be within the manufacturer’s normal operating parameters. Further, if a noticeable voltage fade is observed over time it may be indicative of damaged cells within the battery.
- Coolant and other fluid systems must be drained when possible.
- Any other concerns that arise during the storage of the battery should be discussed with the project point of contact before shipment to Sandia.

3.2 Data

Sufficient data will be required to ascertain with reasonable confidence that the battery is safe for preliminary testing. At minimum, pack voltages before and after NCAP testing should be collected to demonstrate a low likelihood of electrical damage to the cell and external temperature monitoring to watch for evidence of self-heating. Also of value would be voltage

and temperature monitoring of individual cells to give a clearer picture of the state of health of individual cells and/or modules.

3.2.1 Data Available

Data has been provided for a select number of cells that has been collected before and after NCAP testing. Some representative data is shown below in Tables 1 and 2. This data was collected prior to an NCAP roll test (Table 1) as well as after completion of the roll test (Table 2). The data was collected from information available in the on-board battery control system and was collected over ~700 ms. This data shows that there was no change to the pack voltage as a result of the roll test. While this battery was observed during the monitoring period to confirm its state of health, it does not show any immediate signs of electrical damage. Individual cell data (not shown here) as well as internal temperatures is also available.

3.2.3 Additional data requirements

The data described above is not available for every pack in question. The data that has been acquired has been collected using the on-board diagnostic information through the available communication ports. In some instances, it has not been possible to obtain the assistance from the battery manufacturers necessary to access the on-board diagnostic systems of some battery packs. This makes it difficult to determine a general level of health of the battery prior to any testing and also impacts the potential value of the data that may be collected. These impacts are discussed further in section 4.

Table 1. Data collected prior to NCAP roll test

Time (s)	Pack voltage (V)
0	329.775
0.04001	329.775
0.08001	329.775
0.12001	329.775
0.16002	329.775
0.20003	329.775
0.24004	329.775
0.28005	329.775
0.32005	329.775
0.36006	329.775
0.40007	329.775
0.44008	329.775
0.48009	329.775
0.52009	329.775
0.56009	329.775
0.60009	329.775
0.64009	329.775
0.68009	329.775
0.72009	329.775
0.7601	329.775

Table 2. Data collected following NCAP roll test

Time (s)	Pack Voltage (V)
0	329.775
0.04001	329.775
0.08001	329.775
0.12002	329.775
0.16003	329.775
0.20004	329.775
0.24004	329.775
0.28005	329.775
0.32006	329.775
0.36007	329.775
0.40007	329.775
0.44008	329.775
0.48009	329.775
0.52009	329.775
0.56011	329.775
0.60011	329.775

3.3 Review and Acceptance Process

All data on battery condition and state of health will be reviewed by Sandia battery safety SMEs and management who will make the final determination concerning acceptance of test articles. This review will follow the criteria listed above.

4. PACK TESTING

Various testing will be possible on the posttest articles received that is dependent on the level of access to the battery system available. This is discussed here as four general categories of access available to the battery system: 1) external access only, 2) access to monitoring through the battery control system and available CAN bus, 3) independent electrical access to cells or cell groupings along with internal thermocouples and the ability to bypass any on-board battery control system, and 4) disassembly and removal of individual cells or cell groupings for testing.

Typical tests that are run are described by several abuse testing standards, including the USABC Abuse Testing Manual, SAE J2464 “Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing” and UL2580. [3-5] The principal abuse tests conducted include thermal abuse, mechanical abuse and electrical abuse. The referenced standards and manuals list relevant monitoring needs and how typical tests will be affected by limited access to a battery are discussed below. Additional testing not covered by the listed testing standards may include advanced battery diagnostic techniques as well as other abuse techniques, such as analysis of cell failure propagation through a battery. These are discussed as relevant below.

All work performed would also fall under Sandia work planning and control (WP&C) practices, including failure mode effects analysis and implementation of engineered safety controls. It should be noted that this may add significant time and resource requirements to any project involving high hazard activities.

4.1 External access only

This case involves testing that can be done with no access to either the interior electric connections or the CAN bus. This limits monitoring to temperatures measured through external temperature monitoring and possibly the pack voltage from the main terminals; large format EV and PHEV packs typically use contactors that disable voltage to the main terminals when the battery is not in use, however some lower voltage battery packs may have the pack voltage always available. The following testing could reasonably be done.

4.1.1. Thermal abuse

Thermal abuse could be performed using external temperature sensors to monitor the thermal response with open circuit voltage monitoring from the main terminals (if possible). Heat would be applied from an external source to initiate thermal failure of the battery. Collection of data would primarily be limited to external temperature sensing such as thermocouples mounted to the external surface of the battery pack. Monitoring of pack voltage from the main battery terminals may be possible in some cases, however high voltage PHEV and EV battery packs typically disable voltage to the main terminals when the pack is disconnected and not in use; this would prohibit monitoring of pack voltage.

The primary value of such testing would be to observe the response to a large scale failure event such as a vehicle fire. However, while the thermal response could be monitored relatively easily without electrical access to individual cells or the battery pack, little could be inferred about the mechanisms of failure.

4.1.2 Mechanical abuse

Mechanical abuse coupled with external monitoring would be able to monitor the impact of large scale mechanical deformation. Mechanical abuse testing could include both full scale crushing as well as localized crushing of the battery pack until failure. Other potential tests include penetration with a sharp nail or spike as well as mechanical shock or impact.

Data collection again would primarily be limited to external temperature monitoring and visual observation of the pack during testing. Collection of voltage data would be limited to those packs where the pack voltage is always available. Large packs that do not fail as a result of testing may be relatively costly to dispose of as there would not be a method available to adequately determine their state of health and would likely have to be subjected additional abusive tests to cause battery failure and bring the battery to a safe state.

4.2 Access to battery control system monitoring

This case is the testing that can be done with access to the on-board battery monitoring system through the CAN bus. This would allow monitoring of voltages, temperatures and other data monitored by the available control hardware. There would still be limitations in electrical access, as a current could only be applied through the main battery terminals, and protections built into the battery control system may make performing certain abuse tests difficult or impossible.

4.2.1 Thermal abuse

Thermal abuse could be performed in this case by applying an external heat source to the battery until reaching a specified temperature or battery failure. Access to the battery control system in this case would allow the monitoring of internal temperature, voltage and state of health monitoring built into the battery system. Variability in system designs would create some variability in the amount of data that could be collected from cell to cell.

4.2.2 Mechanical abuse

Mechanical abuse coupled with external monitoring would be able to monitor the impact of large scale mechanical deformation. Mechanical abuse testing could include both full scale crushing as well as localized crushing of the battery pack until failure. Other potential tests include penetration with a sharp nail or spike as well as mechanical shock or impact.

Access to the battery control system would allow the monitoring of internal temperature, voltage and state of health monitoring built into the battery system. It should be noted that mechanical abuse testing is highly likely to do some level of damage to the battery control system, ranging from loss of individual data channels to the disabling of the entire battery control system. Further data collection in this event would be limited to external temperature monitoring and visual observation.

4.2.3 Electrical abuse

Access to the battery control system would allow electrical abuse testing on the battery pack. Testing would be limited to whole pack testing as electrical current could only be applied to the main battery terminals. Monitoring would include external temperature monitoring and visual observation as well as internal temperature, voltage and state of health monitoring available

within the battery control system. This would likely require defeating electrical safeguards in place in the battery and would require assistance from the battery manufacturer.

4.3 Internal electrical/thermocouple access

This condition covers configurations where independent electrical access to cells or cell groups is available as well as access to internal temperature monitoring hardware (thermocouples, RTDs etc.). This would allow advanced diagnostics of cells and evaluations of the impact of abuse tests on individual cells or groups within the battery.

4.3.1 Thermal abuse

Application of heat for thermal abuse would still be limited to external heat applied to the entire pack. However, having internal electrical and thermocouple access would allow for more detailed monitoring of the pack. Monitoring of individual cells or cell groupings along with internal thermocouples would allow monitoring of the progression of thermal runaway within the cell and help to determine whether or not the entire battery was engaged by the thermal event.

4.3.2 Mechanical abuse

The mechanical tests that could be performed in this case would not be different than those in other cases and would include large scale crushing, puncture with a sharp nail or spike and mechanical shock or impact. The primary difference in this case would be the data that could be recorded. Mechanical testing may engage only a limited number of cells within the battery. However, due to damage to the electrical systems that can occur during mechanical abuse testing it can be difficult to truly evaluate the condition of the cells after a mechanical abuse test, particularly large scale crushing of the battery. Electrical access to individual cells/cell groups would make it more likely that their states could be evaluated after significant macroscopic mechanical damage has been inflicted on the battery.

Mechanical testing may also initiate a relatively localized failure within the battery that then spreads to other cells. This propagation can be difficult to observe without the ability to monitor the internal electrical and thermal behavior of the battery pack.

4.3.3 Electrical abuse

Independent electrical access to cells or cell groups would allow not only the electrical abuse of the battery pack but also of individual cells and cell groups.

4.3.4 Propagation testing

Internal electrical access would allow for the studying of the effects of failure propagation through the battery pack. While the incidence of failure for commercial lithium ion cells is very low, there is the possibility that a single defective cell within a battery fails with sufficient energy release or damage to the battery system to cause a cascading failure through the pack that engages the remaining cells in the battery.

This test would be performed by introducing a failure to an individual cell or cell group within the battery. One method to cause this failure is to apply an abusive test to the target cell. An overcharge could be applied through the electrical connections available in this case. Mechanical intrusion may be an option to fail a single cell depending on the location within the pack as well

as physical layout of the battery. An external short circuit could be applied as well through the available electrical connections.

4.3.5 Advanced cell diagnostics

Electrical access to cells that bypasses the battery control system would provide the opportunity to perform advanced diagnostic tests on individual cells. This would allow better determination of the state of health of batteries both as received as well as after testing. For example, electrochemical impedance spectroscopy (EIS) is a powerful tool for determining the condition of an individual cell, but the data is easily convoluted by both electrochemical interactions from other cells as well as behaviors of any attached electrical system. Because of this, obtaining meaningful data would require direct electrical access to individual cells. This would allow exploration of the mechanisms of cell failure as well as determination of the impact to cells during an event.

4.4 Disassembly/removal of cells and cell groups

Testing on battery packs could be completed as well by disassembling the packs and harvesting individual cells or cell groups for further testing. This would completely bypass any on-board battery control system and allow for direct testing of cells. However, as the cells would be removed from the pack it would no longer be possible to test impacts of failure of single cells on the larger pack. Further, the disassembly would be a complex process that would likely have to be performed by a third party familiar with such operations.

4.4.1 Abuse testing

Disassembly of the battery pack would provide individual cells that could be evaluated for safety and abuse performance. This would provide a source of the same cells used within the battery packs that could be evaluated under the standard battery of abuse tests as detailed in the USABC testing manual, SAE J2464 or UL 2580. [3-5]

4.4.2 Advanced cell diagnostics

Removal of cells would allow for advanced cell diagnostic tests and state of health monitoring to be performed on individual cells. However, it is unlikely that the cells would be removable in a battery pack that has been previously abused, so this would be limited to diagnostic testing of cells presumed healthy. This would be primarily useful in determining baseline data of cell health to compare from data collected after or during abusive tests. This testing would be available for cells subjected to abusive testing per 4.4.1, but not for cells subjected to abusive testing at the pack level.

4.4.3 Pack disassembly concerns

Disassembly of battery packs would be a complex process and may add significant costs to a project. This would likely need to be performed by a third party contractor with experience in such matters. Ideally, this would be done under the guidance of the battery manufacturer as well to provide an appropriate safe method for extracting the cells from the battery.

5. CONCLUSIONS

Transport of batteries to Sandia is possible, however the nature of the NCAP testing the batteries have been subjected to means that all of the batteries involved would have to be considered damaged. It is still possible to transport these batteries to Sandia, either by obtaining a DOT exemption or by re-obtaining the UN certification of the batteries by subjecting them to the appropriate tests. Correspondence with NHTSA has indicated that exemption permits are already in place for many or all of the batteries in question.

The greatest uncertainty lies in the potential value of the data collected. Without at least some support from the manufacturers of the battery packs the potential data collection would be extremely limited. Some evaluation of the response of the battery to an external event would be possible, such as likelihood of the entire pack being engaged during a fire or large-scale mechanical crush/impact. However, evaluation of the internal state of health of the cell would not be available, and many desired tests, such as propagation of a single cell failure, would not be able to be evaluated.

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