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Electric Vehicle (E-Vehicle) Crash Test Lab Safety Guidelines

RATIONALE

This document has been updated to address the need for using gloves to prevent shock. Other changes were to update the document to the current SAE format.

INTRODUCTION

Current E-vehicles in production and in various stages of development share many obvious characteristics with their internal combustion cousins. Crashworthiness is certainly one of these, requiring that—regardless of the power source—all passenger vehicles must demonstrate compliance with manufacturer driven performance standards, government-regulated crash test programs, and certain vehicle safety rating programs which provide information to potential buyers about the crash performance of the vehicle and other features related to safety.

The electric vehicle is certainly not a new concept, but it has shown significant growth in development, production, and sales over recent years. The current administration has promoted the increase of E-vehicles on U.S. roadways as a means to promote further development of this technology, reduce greenhouse emissions, and decrease the nation's dependence on foreign oil. Significant federal and corporate funding has been provided to help support lithium-ion (li-ion) battery research, establish infrastructure, and incentivize vehicle purchases. Parallel to these efforts, there is work ongoing to understand special risks to the general population, emergency responders, and automobile repair centers associated with the li-ion battery systems in these vehicles following roadway collision events.

This SAE Information Report addresses the special risks associated with E-vehicle collisions in the lab, which must be conducted not only on the final product as a means of certification or rating, but also throughout the development phase of the vehicle. The hazards associated with running crash tests on internal combustion vehicles (ICVs) is well understood and managed safely using established test protocol which requires testing to be conducted with surrogate, less flammable fuel in the vehicle. Some special risks are associated with pressurized tanks in natural gas, propane, and hydrogen vehicles, but these are outside the scope of this report.

As stated in the scope of this report, the unique risks associated with conducting crash tests on E-vehicles can be divided into two main categories: (1) thermal activity inside the battery (resulting from electrical or mechanical abuse) may lead to energetic emission of harmful and/or flammable gases, thermal runaway, and potentially fire; and (2) the risk of electrocution. Specific measures to ensure protection to test personnel from all types of risk must be integrated into the entire test process from the point the vehicle arrives at the test facility up to the time it is hauled away. At this point in time, relatively mature procedures exist to protect against electrocution, utilizing personal protective equipment (PPE) rated for high voltage safety, and careful electrical measurements to ensure safe conditions when handling the vehicle both pre- and post-crash. These procedures are described in detail in this report.

Current U.S. regulations require vehicle crash tests, when conducted for the purpose of certification, be run with fully operational and fully charged battery systems. The level of risk assumed by the crash test lab is determined by the degree to which a specific li-ion battery system is susceptible to failure during mechanical abuse (shock, puncture, crush), or electrical abuse (internal or external short circuit), experienced during each type of test. As battery system design/technology advances, the level of risk will likely also be affected.

In summary, there is some level of risk that every facility will assume in conducting these tests, so each lab must establish its own safety procedures and determine its own risk tolerance. More data will help make decisions that can mitigate risks to personnel and reduce the chance of additional loss in the event of a total system failure.

1. SCOPE

The special risks associated with conducting crash tests on E-vehicles can be divided into two main categories: (1) thermal activity inside the battery (resulting from electrical or mechanical abuse) may lead to energetic emission of harmful and/or flammable gases, thermal runaway, and potentially fire; and (2) the risk of electrocution. Procedures to ensure protection from all types of risk must be integrated into the entire crash test process. This SAE Information Report is intended to provide guidance in this endeavor using current best practices at the time of this publication. As both battery technology and battery management system technology are in a phase of expansion, the contents of this report must then be gaged against current technology of the time and updated periodically to retain its applicability and usefulness.

The scope of this document is to provide an understanding of the risks and an overview of the techniques established to reduce the likelihood that an event would cause harm to laboratory personnel and/or property. A laboratory considering E-vehicle crash testing should work closely with the E-vehicle manufacturer to identify and understand the risks associated with shipping and handling of their vehicle (pre- and post-crash), storage of the vehicle (pre- and post-crash), battery system diagnostics procedures, and operation of the vehicle.

2. REFERENCES

2.1 Applicable Documents

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

2.1.1 SAE Publication

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J1715/2 Battery Terminology

2.1.2 Code of Federal Regulations (CFR) Publications

Available from the United States Government Printing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.gov.

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

TP 305 Laboratory Test Procedure for FMVSS 305, Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 Other Publications

Arora, P. and Zhang, Z. “Battery Separators.” Chem. Rev., 2004, 104, 4419-4462.

Hammami, A., Raymond, N., and Armand, M. “Runaway Risk of Forming Toxic Compounds.” Nature Publishing Group, 2003, 424, 635-636.

Long, T.R. Jr., Sutula, J.A., and Kahn, M.J. “Li-Ion Batteries Hazard and Use Assessment Phase IIB: Flammability Characterization of Li-Ion Batteries for Storage Protection.” Exponent, Inc. The Fire Protection Research Foundation, April 2013.

Sturk, D., Hoffmann, L., and Tidblad, A.A. “Fire Tests on E-Vehicle Battery Cells and Packs.” Traffic Injury Prevention. doi:10.1080/15389588.2015.1015117.

Wang, Q., Sun, J., Yao, X., and Chen, C., “Micro Calorimeter Study on the Thermal Stability of Lithium-Ion Battery Electrolytes.” Journal of Loss Prevention in the Process Industries, 19, 2006, 561-569.

Wech, L., Richter, R., Rainerr, J. and Schoneburg, R. “Crash Safety Aspects of HV Batteries for Vehicles.” 22nd ESV Conference, 2011-0302.

Wilken, S., Treskow, M., Scheers, J., Johansson, P., and Jacobsson, P. “Initial Stages of Thermal Decomposition of $LiPF_6$-Based Lithium Ion Battery Electrolytes by Detailed Raman and NMR Spectroscopy.” RSC Advances, 2013.

Yang, H., Amiruddin, S., Bang, H.J., Sun, Y.K., and Prakas, J. “A Review of Li-Ion Cell Chemisitries and Their Potential Use in Hybrid Electric Vehicles.” J. Ind. Eng. Chem., Vol. 12, No. 1, 2006, 12-38.

Yang, H., Zhuang, G.V., and Ross, P.N. Jr. “Thermal Stability of $LiPF_6$ Salt and Li-Ion Battery Electrolytes Containing $LiPF_6$.” Journal of Power sources, 161, 2006, 573-579.

3. DEFINITIONS

3.1 BMS

Battery management system.

3.2 E-VEHICLE

A vehicle with an electrified drivetrain, such as EVs, HEVs, and PHEVs.

3.3 EV

Electric vehicle.

3.4 HV

High voltage.

3.5 HEV

Hybrid electric vehicle.

3.6 INERT BATTERY

A battery that has the same physical properties as an HV battery pack (dimensions, stiffness, weight), but with no active chemistry (no electrical or thermal risk).

3.7 LI-ION

Lithium-ion battery.

3.8 MSD

Manual service disconnect.

3.9 PHEV

Plug-in hybrid electric vehicle.

3.10 PPE

Personal protective equipment.

3.11 SDS

Safety data sheet.

3.12 THERMAL RUNAWAY

A situation where an increase in temperature changes the conditions in a way that causes a further increase in temperature.

4. MITIGATION OF ELECTRICAL SHOCK RISK (ELECTROCUTION)

4.1 General

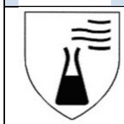
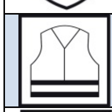
It is recommended that any personnel working with a HV system in a vehicle should have basic HV training on E-vehicle systems such as the “SAE basic hybrid and electrical vehicle safety” class. Knowledge regarding PPE and internal safety procedures in a HV setting is vital in protecting yourself and your facility. Key laboratory personnel should be advised by the OEM or HV battery final assembler regarding their specific battery so that knowledge is transferred to the test facility. This will be discussed in detail below.

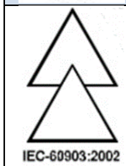
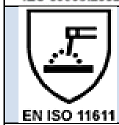
4.2 Personal Protective Equipment (PPE)

PPE for electrical hazards is required when working with a HV system. The work should be done in view of other laboratory personnel. Recommended safety equipment includes, but is not limited to:

- Class 0 HV gloves with protectors. These gloves should be replaced periodically (CFR 29 part 1910.137 requires rubber insulating gloves to be electrically tested on an interval of 6 months) and should undergo a visual inspection and glove pressure test before each use.
- HV insulated tools.
- Face shield.
- HV rescue hooks.
- Electrical shock-resistant footwear.
- Self-contained breathing apparatus (SCBA).
- Protective coverall.
- Gas detection warning device: flammable hydrocarbons, carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), fluoro-organics, and hydrogen fluoride (HF).

Table 1 - Reference table for applicable PPE standards

Symbol	Standard ID	Similar Std	Explanation	Equipment
	ASTM F1506		Flame-resistant garment labeled with an arc energy rating, ATPV.	Coverall
	ASTM F1956	IEC 61482-1-2	Protective clothing against the thermal hazards of an electric arc.	Coverall
	EN 1149		Electrostatic properties.	Jacket, pants
	EN 13034 type 6		Garments that provide a limited protection against liquid chemicals.	Jacket, pants
	EN 136		Respiratory protective devices; full face masks.	Respiratory protection
	EN 140		Respiratory protective devices; half masks and quarter masks.	Respiratory protection
	EN 14387		Respiratory protective devices. Gas filter(s) and combined filter.	Respiratory protection
	EN 166		Eye and face protection.	Eye protection, e.g., glasses, visor/screen guard
	EN 170		UV protection.	Eye protection, e.g., glasses, visor/screen guard
	EN 470-1	ISO 11611	Protective clothing for use in welding and allied processes. General requirements.	Jacket
	EN 471		High-visibility warning clothing.	Jacket, pants
	EN 531	ISO 11612	Protective clothing for workers exposed to heat.	Jacket, pants, bas- and mid-layer clothing
	EN ISO 15090 HI3 F2A P.T.CI		Fire shoes suitable for fire rescue, fire suppression. General Type 2 requirements and antistatic properties.	Boots
	EN ISO 17249		Safety footwear with resistance to chain saw cutting.	Boots
	EN ISO 20345 S5 HRO SB		Safety footwear standards. A + FO + E + P + waterproof resistance to hot contact of outsole toe protection.	Boots
  	ENV 50354	IEC 61482-1-2	Protection against electric arc. Electrical arc test methods for material and garments, for use by workers at risk of exposure to an electrical arc.	Bas- and mid-layer clothing

	Standard ID	Similar Std	Explanation	Equipment
	IEC 61482-1-2	ENV 50354	Protective clothing against the thermal hazards of an electric arc.	Jacket, pants, coverall
	IEC-60903		Electrical insulating gloves.	Gloves
	ISO 11611	EN 470	Protective clothing for use in welding and allied processes. General requirements.	
	ISO 11612	EN 531	Protective clothing for workers exposed to heat.	

4.3 Vehicle Receiving Inspection

HV battery specifications should be discussed with the OEM or final battery assembler before any testing begins. This overview should include the following:

- The areas specified per your safety protocol. Fire extinguishers, HV mats, forklift with insulated forks, safe meeting place should there be an event, etc.

- Battery State of Charge (SOC) and battery health diagnostic procedures should be verified before any work begins. Proper procedures (as provided by manufacturer) should be used if required to charge and discharge the HV battery.

- The HV sub-components are reviewed and identified. Primary focus should address areas that will be in direct contact with the impacted area. Secondary focus will include other HV systems not in direct area of impact. All HV lines should be located and noted in case of emergency removal of the vehicle.

- The manual service disconnect (MSD), if applicable, location is identified. It is recommended that any parts that impede access to the MSD be removed prior to testing.

- First responder locations are identified and reviewed with the entire safety team.

- Identify which parts of the system are energized at each position of the key/ignition switch.

- Define expected post-test conditions of HV system, as well as the procedure used to verify the HV battery is in a non-compromised state.

- Other vehicle or HV system features or risks the laboratory personnel should be aware of when prepping the vehicle, conducting the test, or any post-test inspection or handling of the vehicle or battery system.

4.4 Vehicle Preparation

It is recommended that before any vehicle preparation work begins, the 12 V battery and the MSD are disconnected. An HV monitoring system is installed on the outside of the vehicle for use in assessing/monitoring electrical isolation per FMVSS 305. Care should be taken to ensure no fluids (coolant, brake, etc.) are removed during the preparation processes that are required for the HV system to operate correctly. Prior to test time the 12 V battery and the MSD must be reconnected, and the HV battery system again verified to ensure the battery SOC is correct for testing.

4.5 Pre-Crash Measurements

When performing pre-crash measurements all applicable PPE should be in place and ready for use.

Pre-crash measurements should be taken after completion of the vehicle preparation process (after the MSD is reconnected), and immediately prior to the dynamic test. Precautions should be made to avoid unintended power transmission to the tires and accidental propulsion of the vehicle (could include measures to disable linkages, block shift lever, etc.). Ensure that the test vehicle is in “ready-to-drive” mode, where the battery is connected to the vehicle propulsion system and voltage is being supplied to the electric/hybrid drive. Measurements are then taken in accordance with FMVSS 305 (or equivalent standard/regulation) from the HV monitoring system which has been mounted on the outside of the vehicle. The HV monitoring system measurements should at a minimum include the drive side (downstream) of the safety switch utilized in the electric/hybrid drive system. It is recommended that the battery side (upstream) of the safety switch is also measured, which may require specific OEM equipment and software. These measurements provide a baseline for an isolation check of the battery and the drive system if the safety switch were to open during the crash event.

It is recommended that baseline temperature (inside the battery pack) is recorded at this time. This can include, but is not limited to, the use of thermocouples, IR thermometers, and/or thermal cameras. A visual inspection of any accessible areas of the battery can also be performed. This inspection should focus on any items/liquids that might be confused for battery components/electrolyte after the test.

4.6 Post-Crash Measurements

Approach every post-crash vehicle with all applicable PPE in place and extreme caution.

Immediately following the dynamic event, post-crash measurements need to be taken. Extreme caution should be used until the stability of the HV system can be confirmed. In accordance with FMVSS 305, post-crash measurements from the HV monitoring system should be measured and compared to the pre-crash values. Calculations shall be performed to obtain an isolation value. If any of these measurements confirm a loss of vehicle isolation, the test facility’s emergency response plan shall be activated (see Section 7).

Post-crash temperature values should be compared to the pre-crash baseline measurements. If there is any increase in temperature (beyond expectations) or battery temperature is above the recommended limits supplied by the manufacturer, the test facility should follow their emergency response plan for a potential thermal runaway condition.

A visual inspection of the area around the HV system should be conducted, and should focus on any items not present before the dynamic event. This can include noticeable venting of gasses, unusual odors, any liquids, broken HV components, and any other potential safety hazards. Upon discovery of any unexpected safety hazard, the laboratory should follow its emergency response plan.

After all measurements are complete, and stability of the vehicle is confirmed, the auxiliary battery and the MSD should be removed/disconnected, unless advised otherwise by the manufacturer regarding battery system management.

5. MITIGATION OF RISKS ASSOCIATED WITH THERMAL ACTIVITY (THERMAL RUNAWAY, HAZARDOUS GAS EMISSION, AND/OR FIRE RISK)

5.1 General

For this discussion, the term “E-vehicles” is used to denote all vehicles having complete or partial electric battery powered drivetrain (i.e., EV, HEV, PHEV). Also, only li-ion batteries are mentioned as this technology is most commonly used for E-vehicle applications, and countermeasures designed for these will have significant carryover to other systems. Insofar as the battery pack is the source of concern regarding thermal runaway propagation, energetic release of harmful gases, and/or fire, it is the primary focus for this section.

As would be expected, there is greater variability in system level performance with full vehicle crash tests than in individual component level tests. Similarly, battery system performance in a crash environment is dependent on the level of variability among its individual components. Each battery system, each battery chemistry, and—in some sense—each individual cell within a battery system has its own characteristics and may not respond precisely the same under a given mechanical abuse or short circuit condition. Considering the potential for variability in crash test input conditions (test speed, impact location, track conditions, etc.), variation in vehicle structures (particularly in pre-production phase), and battery systems variability, and given the potential risk that catastrophic failure could result—a margin of safety must be established before crashing a fully or partially charged E-vehicle inside of an enclosed crash test lab. Safety protocol outlined in this report is based on the following priorities:

- First: Personnel safety.
- Second: Facility protection.
- Third: Onboard instrumentation, test dummies, data acquisition system, cameras, etc.

5.2 Battery System Properties

There are numerous configurations and chemistries represented in current li-ion batteries, with more variations to come as technology continues to progress. It is beyond the scope of this report to attempt a summary of these systems or their specific properties, or how each will respond to a given abuse condition. Subsequently, the discussion here is limited to defining the type of information that will be useful in protecting a laboratory and its personnel.

- An SDS (safety data sheet, formerly MSDS) must be provided to the lab prior to receipt of any potentially hazardous chemical (i.e., electrolyte). Information about the chemistry of the battery such as the flash point of the electrolyte and the constituent solvents (e.g., alkyd carbonates—EC, PC, DMC, DEC, EMC, or other organic species) and the constituent salt (e.g., $LiPF_6$) will provide the basic information to assess what type of flammable and toxic gases may be emitted from any ruptured, burning, or venting battery cells.
- Information about the electric capacity and characteristics of the battery cells and the system of interest, and the overall configuration of the cell-strings will help to assess the amount of thermal energy that can be generated in the event of a critical failure (such as a battery pack external, battery pack internal, module external, cell external, or cell internal short circuit discharge). The heat generated in such a failure is often the source which may push the battery into thermal runaway condition.
- Configuration of the battery pack (number of parallel or series-connected cell-strings and how are the cell-strings connected to each other) can also be of use in assessing risk potential.

One of the critical tasks before performing charged E-vehicle tests is to develop procedures that prepare the lab to respond safely in the event of a critical failure (leakage, energetic release of harmful gases, and/or fire) of the battery system. For such a procedure to be considered, the lab must become familiar with the potential risks (electrical, chemical, and thermal) and also have a means to safely detect the level of risk at each point in the process. Typical risk indicators for li-ion batteries are:

- Increase in temperature.
- Smoke or other unordinary odors.
- Electrolyte leakage.
- Observable physical damage (such as deformation, puncture).
- Increased levels of carbon monoxide and possibly hydrogen fluoride.

Of these, rising temperature is currently considered to be the preferred sign of potential risk, as it can be detected early and is also quite easy to monitor remotely (without exposing personnel to possible danger). Ideally, the temperature should be monitored remotely (from safe area) through the vehicle's battery management system (BMS). At a minimum, however, thermocouples should be installed by the OEM to monitor temperature change within the battery pack. The number and placement of thermocouples should provide test personnel with the earliest possible warning of thermal instability within the batter pack. The data should then be transmitted remotely to a safe area where it can be monitored post-crash for any thermal activity.

In addition to temperature change, it is also recommended to monitor closely for visible smoke or odors. It may also be helpful to monitor changes in carbon monoxide and hydrogen fluoride levels, as both can reach harmful concentrations during critical failure of a li-ion battery. Gas analysis equipment is available commercially for these gases.

6. RISK MITIGATION TESTS

6.1 General

When considering whether to conduct live E-vehicle crash testing (especially in an enclosed lab), the level of risk that is acceptable must be determined (tolerance for some level of risk that a thermal event may result). A thorough risk analysis and cost/benefit may need to be conducted for the test vehicle under consideration before determining if the risk is reasonable. In some instances, the facility's insurance coverage may require certain countermeasures be in place prior to testing. If the risk tolerance is zero, then the crash testing should be rejected on these vehicles until destructive performance data can be provided to support the zero risk policy. To establish confidence in the system to be tested, it is strongly recommended that each test mode be evaluated independently.

6.2 Inert Battery Vehicle Crash Tests (Generally Conducted During Development Phase)

To understand the environment in which the battery must survive during a vehicle crash test, each targeted crash test mode should be conducted with an "inert" battery installed. The "inert" battery should mimic the physical properties of a "live" battery pack (dimensions, weight, stiffness, etc.) but contain no active chemistry. During these crash tests, the following observations can be made:

- Integrity of the battery mounting system.
- Relative margin of safety against battery pack intrusion/deformation offered by the existing vehicle structure.
- Integrity of the battery case to withstand crash acceleration, and loads generated by relative movement/deformation of battery attachment points within the vehicle structure.
- Acceleration pulse the battery pack sees in each crash mode.
- Access to the MSD, if applicable, following the crash.
- Safe location to mount an external junction box with which pre- and post-test battery electrical integrity tests will be made. Also determine safe routing of the patch cables between the junction box and the battery pack.
- Effect of crash on accelerator and shift lever linkages so effective precautions can be made against unintended power transmission to the tires during a test or during test setup.
- Verify battery temperature and electrical measurement process, and train technical staff.
- Verify emergency response procedures (dry runs during inert tests).

The inert battery crash tests can be repeated as needed until a sufficient margin of safety is achieved.

6.3 Battery Component and Sub-System Tests

Based on the conditions the battery will be subjected to in a crash, component level battery tests should be conducted to establish a satisfactory margin of safety for the battery pack and for the configuration of cells contained within.

Component functional tests should be considered based on industry standard tests, or on the observations made during the "inert" battery vehicle crash tests or by use of validated CAE crash simulation models—whichever is more severe. Criteria for these tests will generally require that the battery system remain stable, that the structural integrity of the pack is sufficiently maintained, and that there is no leakage. Typical functional tests may include:

- Mechanical shock in each direction of each mutually perpendicular axis.
- Mechanical crush (dynamic).
- Puncture/pierce test (dynamic).