Lithium ion Based Rechargeable Energy Storage System (RESS) Safety Performance Measurement in Automotive Applications Test Plan

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ABSTRACT

In response to the planned increased availability of Li-ion based electrically propelled vehicles, NHTSA has initiated a safety research program. This programs' plan will assess the safety risks associable to Li-ion based rechargeable energy storage systems (RESS) during all operating conditions. NHTSA's plan is to analyze failure modes through a failure modes and effects analysis (FMEA), develop repeatable test procedures and safety metrics to measure effect of the failure modes, and analyze the performance characteristics of an effective RESS control system.

INTRODUCTION

The RESS is a completely functional energy storage system consisting of the battery pack(s), and necessary ancillary subsystems for physical support and enclosure, thermal management, and control, including electronic control. The automotive application and use of a RESS, such as a Lithium-ion battery based system, imposes certain theoretical safety risks to the operators and occupants of these vehicles because it is inherently different compared to that of vehicles using only an internal combustion engine. None of the safety risks associated with lithium-ion batteries have been demonstrated in the field since these batteries have had very limited field exposure to date. Hence all safety risks for these systems must be considered as theoretical or potential risks. Among the most severe potential safety risks are the failure modes which result in "thermal runaway" of an affected cell(s) or battery pack(s) which in some cases may result in potentially toxic effluent gas venting, fire, or explosion. These potential safety risks can be associated to the responses of undesired or unexpected abuse mechanisms during both normal and abnormal operating conditions. These abuse mechanisms originate in mechanical (i.e., shock, vibration, crush, penetration, or immersion), thermal (i.e., radiant heat, extreme ambient, or thermal shock), or electrical (i.e., short circuit, over-charge, or undercharge) conditions and/or environments.
These conditions may arise as a result of failure of specific RESS control and support hardware, operator negligence, vehicle traffic accidents, device or system defects, poorly informed or trained users or repair technicians, or transportation handling incidents. These potential safety risks may be observed in many operational modes and conditions including: storage, charging, normal vehicle operation, vehicle crash, and/or post crash conditions.

BACKGROUND

Due to significant advancements in Rechargeable Energy Storage Systems (RESS) the viability of electrically powered propulsion for use in passenger vehicles, light trucks, and multipurpose vehicles in the automotive industry have greatly

improved. The automotive applications of Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), and Electric Vehicle (EV) propulsion systems represents a measureable and growing technology segment necessary for achieving increased demand for improved fuel economy, reduced green house gas emissions, and reduced dependence on foreign oil.

The U.S. Department of Energy (DOE) has been actively involved with battery, module, and cell characterization and performance testing through efforts with Sandia National Laboratories (SNL) and the Idaho National Engineering and Environmental Laboratory (INEEL) since 1973. In July 1999 SNL published the *Sandia National Laboratories Electrochemical Storage System Abuse Test Procedure Manual* [1]. The procedures in the manual were developed to characterize the performance of a RESS relative to the U.S. Advanced Battery Consortium (USABC) long-term battery requirements. The test procedure manual describes three levels of testing, low-level or common events where the RESS is expected to remain intact, mid-level tests were the RESS may become inoperative but not expose any known health risks, and high-level tests which result in destructive situations. The test procedures described in the report are intended to simulate actual use and abuse conditions (mechanical, electrical, and thermal) and internally initiated failures that may be experienced in a RESS. These tests were derived from Failure Modes and Effects Analysis (FMEA), user input, and historical abuse testing. Test procedure parameters were developed and are described in the general information of the SNL manual. Among these parameters, the SNL manual describes that the RESS test article shall be in fully charged state, at normal operating temperature, with cooling media in place, and with thermal control systems running, unless specified otherwise. These and other conditions and permutations including system age and level of assembly are based are based on the most susceptible condition of the technology.

In 1999 The Society of Automotive Engineers (SAE) published SAE J2464 *Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing* (revised 2009) [2] which adopted test procedures from the *Sandia National Laboratories Electrochemical Storage System Abuse Test Procedure Manual* as a basis for a body of tests which may be useful for abuse testing of electric or hybrid electric vehicle batteries to determine the response of such batteries to conditions or events which are beyond their normal operating range. However, neither SAE J 2464 nor the SNL Electrochemical Storage System Abuse Test Procedure Manual had intent of addressing performance acceptance criteria.

In February, 2011 SAE published SAE J2929 *Electric and Hybrid Electric Propulsion Battery System Safety Standard – Lithium Based Rechargeable Cells* [3] which describes performance criteria for some of the tests described in SAE J2464. These test procedure manuals and standards developed and published by SNL and SAE will serve as a foundation for consideration by NHTSA in developing performance based test procedures, safety metrics, and acceptance criteria.

SCOPE

The scope of the NHTSA RESS safety research program is to develop safety test methods and performance base safety-metrics to measure and compare Li-ion

based RESS technologies. The program will include identifying and documenting appropriate test conditions, boundary limitations, and performance criteria that can be applied to vehicle level testing when possible, component level when necessary, or both. The RESS configurations in this program will be inclusive of and limited to presently identified Li-ion based RESS and foreseeable advanced electrical energy storage devices or battery technologies, to be utilized in a HEV, PHEV, or EV application on a passenger car, light truck, or multipurpose vehicle; while not unnecessarily limiting them to an individual or unique chemistry composition, cell format or construction, or cell arrangement. Utilizing test procedure and RESS development experience, the NHTSA safety research intends to develop and demonstrate meaningful, comparable, and quantitative evaluations that will link test procedures to failure modes associated with component failure, control system failure and/or induced faults from potential abuse mechanisms or conditions.

RESEARCH PLAN

For purposes of providing the most comprehensive research approach, NHTSA vehicle safety research will initiate three independent research projects.

1) An Analytical Approach (FMECA)
A Failure Modes and Effects Analysis (FMEA), is a bottom up analytical process, typically used in product development, of potential failure modes within a functional system for classification by the severity and likelihood of the failures. A successful FMEA activity helps to identify potential failure modes based on past experience with similar products or processes. A Failure Modes, Effects, and Criticality Analysis (FMECA) builds on the FMEA by including a criticality analysis, which is used to chart the probability of failure modes against the severity of their consequences. The result highlights failure modes with relatively high probability and severity of consequences, allowing remedial effort to be directed where it will produce the greatest value. This FMECA will be published as a standalone document and be used as a foundation for the analytical control system study.

2) Develop physical test procedures.
This NHTSA RESS safety research program is to develop and document repeatable vehicle level safety performance tests procedures with accurate boundary and/or test limit conditions for the battery pack (component level) and/or vehicle in which the testing should be conducted. In addition, detailed quantifiable measurement, performance criteria, and safety-metrics must be developed and documented. These test procedures may be used by NHTSA to objectively measure and compare safety performance of a RESS equipped vehicle or component system in their analysis.

The safety performance tests and methods shall address potential failure modes associated with RESS component failure, control system failure, and/or reaction to potential normal and abnormal thermal, mechanical, or electrical abuse conditions and their associated limitations. Failure modes such as thermal ramp up or thermal runaway of the battery cells, modules, pack(s), that could result in potentially toxic or harmful effluent venting into a vehicle passenger compartment, fire, or explosion will be examined. The research will consider all functional modes of operation including charging, storage, normal operation, and abnormal operation such as crash and post crash events. When possible, these methods will be considered at vehicle

level but component level test methods will be considered when necessary.

The first phase of this research will focus on single point failure modes based on mechanical, electrical, and thermal abuse mechanisms potentially experienced by the RESS during normal and abnormal operating conditions described in but not limited to SAE J2464, and SAE J2929.

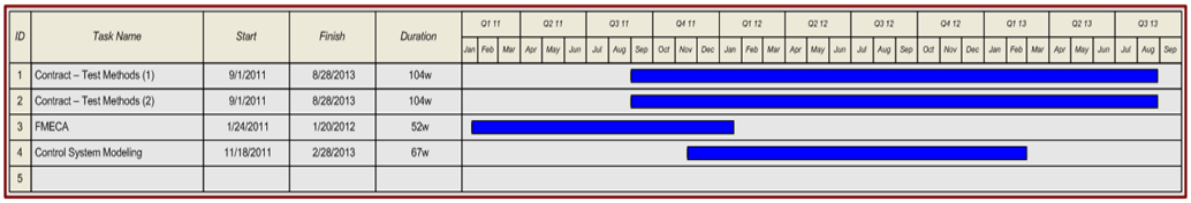
The second phase will focus on multiple point failure modes in which one of the failure modes is identified as loss of control or loss of function of the active portion of the control system, and the second mode as one described in but not limited to those described in SAE J2464, or SAE J2929. During both phases of this research, the resultant response of an individual cell to many of the imposed abuse mechanisms or failure modes is generally assumed to be that of thermal runaway. Since the cells or modules are a part of a greater RESS and/or entire vehicle subsystem, in both phases of test development, a comprehensive layered safety approach will be evaluated. The first priority is to quantify the effect of the failure as a function of safety to the vehicle occupants, second to measure the RESS system effectiveness at containing the failure to the enclosure and the quantified effect of the failure mode with respect to adjoining cells and physical surroundings in the form of thermal and/or mechanical propagation and the measured effect to the entire vehicle system.

3) <u>Analytical Tools and Control System Modeling</u>

Using the analytical results from the FMECA combined with those from a Fault Tree Analysis (FTA), a generic high level analytical tool utilizing control models will be developed for each of the configurations (HEV, PHEV, and EV). The use of this analytical model tool will be to define potential minimal control system performance requirements in terms of redundancy and passive protection for each of the major failure modes. Second, the model will be researched for use as a tool for functional comparison to an OEM control system in the event of field failures.

RESEARCH PLAN (TIMELINE)

NHTSA plans to award two contracts to begin the research this year and complete it during 2013. NHTSA has awarded the FMECA in January 2011 with a projected 12 month completion date. The control system model, which is heavily reliant on the FMECA, is projected to begin in the first quarter of the 2012 fiscal year.



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SAND99-0497 *Sandia National Laboratories Electrochemical Storage System Abuse Test Procedure Manual* (http://prod.sandia.gov/techlib/)

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[3] The Society of Automotive Engineers, 400 Commonwealth Drive Warrendale, PA 15096-0001 USA
SAE J2929 *Electric and Hybrid Electric Propulsion Battery System Safety Standard – Lithium Based Rechargeable Cells*
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