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A review of international abuse testing standards and regulations for lithium ion batteries in electric and hybrid electric vehicles

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ABSTRACT

Lithium ion batteries are a proven technology for automotive applications and their continued use in the future electric vehicle fleet is undeniable. In addition to battery performance and durability, battery safety is paramount to ensure confidence and widespread adoption of electromobility in our society. This comprehensive review aims at presenting the various international standards and regulations for safety testing of lithium ion batteries in automotive applications under various abusive environments. Safety tests are presented and analysed including mechanical, electrical, environmental and hazards of chemical nature. The intention of this review is compiling the most relevant standards and regulations to identify shortcomings and areas for future improvement.

1. Introduction

Reducing carbon dioxide emissions is a major driving force for the displacement of traditional internal combustion engines (ICE) based on fossil fuels by "greener" and more efficient alternatives. In this context, various measures within the policy framework are being established internationally to accelerate the development and adoption of vehicles based on alternative fuels. Based on these efforts, it is expected that the electrification of transport will make up a significant share of the near future automotive fleet [1]. According to the Report "Competitiveness of the EU Automotive Industry in Electric Vehicles" published in 2012 [2] the European Union (EU-27) will reach 14.8 million new light duty vehicle registrations (passenger cars and light commercial vehicles) by 2020, of which 7% will be electric vehicles (including Battery Electric Vehicles, BEVs, plug-in Hybrid Vehicles, PHEVs and Fuel Cell Vehicles, FCV). This market share is foreseen to rise to 31% by 2030 with Europe, Japan and U.S. expected to be leading markets. Other studies considering moderate policy support and technical advancement present 5–10% of the market share in the 2025–2030 time frame [3]. Global registrations of FCVs will still be under 1% in 2030, thus battery driven vehicles will dominate the EV market in the near future.

In 1991 Sony launched the first commercial lithium ion batteries (LIBs) [4]. Since then it has emerged as the dominant energy storage technology used in most consumer electronics (e.g. cell phones, notebooks) [5]. Moreover, LIBs are used to power several electric vehicles available on the market, e.g. BMWi3, Tesla Model S, Nissan Leaf, Mitsubishi iMiEV, Chevrolet Volt, Renault Zoe. The widespread deployment of this technology is reinforced by its relatively high specific energy and power density and its progressive cost reduction, with estimations from ~ 800 \$ kW h^{-1} per pack in 2010 down to ~ 248 \$ kW h^{-1} by 2030 (for a 21 kW h BEV) [6] based on the current chemistries. Predictions assume that by 2020, LIBs will be used in 65% of the total EV systems, surpassing other technologies, including NiMH [7].

Many battery standards and regulations have been specifically developed to facilitate and regulate battery use in EVs. At this stage it is useful to differentiate between standards and regulations. Standards are in principle voluntary documents, drafted by non-governmental organisations such as the International Electrotechnical Commission (IEC), the International Organisation for Standardisation (ISO), the Society of Automotive Engineers International (SAE) at international level and the European Committee for Standardisation (CEN) and European Committee for Electrotechnical Standardisation (CENELEC) at European level. Standards can also be issued by National bodies (e.g. British Standards Institution (BSI), Japanese Industrial Standards Committee (JISC)) or regional organisations. Regulations, on the other hand, are issued by governmental authorities and have the force of law. For road vehicles, the most relevant regulations are type approval

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regulations issued by the United Nations Economic Commission for Europe (UNECE). These regulations define uniform technical prescriptions for wheeled vehicles, their parts and equipments, and state conditions for reciprocal recognition of type approvals by several countries. In the USA, the National Highway Traffic Safety Administration (NHTSA) issues regulations via the Federal Motor Vehicle Safety Standards (FMVSS), setting minimum safety performance requirements for motor vehicles or items of motor vehicle equipment.

Standards may be referred to by laws and regulations. For several technical domains, Europe now follows the so-called New Legislative Framework (NLF) adopted in July 2008, which built on the "New Approach", where directives only mention essential requirements, while technical details are specified in harmonized European standards referred to in these directives. Conformance to these standards subsequently implies conformity to the essential requirements of the directive. The NLF is used for example in the Low Voltage Directive, but not yet for road vehicles, for which UNECE type approval regulations are used. The Motor Vehicle Type Approval (EC Directives) allows national type approvals and subsequently ensures recognition of this approval in other EU member states, i.e. if one vehicle is type approved in one member state, it is allowed to be sold in any other member state.

In 2012, EU and US standards organisations agreed a Transatlantic Cooperation on Standards for Electric Vehicles to avoid proliferation of conflicting electric vehicle and battery safety standards. The cooperation sets the basis towards harmonisation and alignment of standards in the field of electromobility [8]. The need for such harmonisation of battery standards for automotive applications has been acknowledged by others who suggest that performance and safety can hence be improved [9].

Battery safety standards and regulations call for testing in abusive conditions. In these situations (e.g. overcharging, short circuit, physical deformation in a vehicle crash) exothermic reactions may be triggered (e.g. temperature rise of hundreds of degrees within seconds [10]) leading to thermal runaway. This can lead to the heating up of neighbouring cells within a module, which – if sufficient heat is generated – can lead to a chain reaction and propagation [11,12], and in a worst case scenario, develop into fire and explosion [13–15]. Most of the time LIBs behave as foreseen during their lifetime. However a number of highly publicized LIB safety events have led to hazardous situations making the evaluation of battery safety a key aspect in battery development. Events such as laptop fires [16], smoking cell phones [17], airplane incidents [18–21], the GM Volt fires [22], ground impacts leading to safety events on Tesla Model S [23], although scarce, reach the media much easier than events with established technologies (i.e. internal combustion engine vehicle fires). Such events have led to withdrawal of products from the market (e.g. Apple removed lithium ion power packs from their PowerBook 5300 line [24], CPSC and EV Global Motors Company announced the recall of 2000 batteries in their electric bicycles [25]) which may generate an increased concern from the general public towards lithium ion technologies in general. The link between safety related events and the market uptake of battery driven EVs is of concern to battery producers, vehicle original equipment manufacturers (OEMs) and transportation policy makers.

The objective of this review is to compile the most relevant standards and regulations dealing with abuse testing of LIBs. Safety risks specific to LIBs are summarized (Section 2). Test methods in these standards and regulations are classified according to the nature of the misuse conditions applicable (Section 3). Test parameters and conditions used in test methods are compared – commonalities and differences are highlighted (Section 3). Relevant forthcoming standards and regulation are listed (Section 4). Stemming from these comparisons, conclusions are drawn identifying areas for improvement with respect to the relevance and fitness for purpose of existing tests for electric vehicles (Section 5). Shortcomings and suggestions for future development are also identified (Section 5).

Table 1
List of typical components in lithium ion batteries (LIBs).

Cathode	LMO, LCO, NCA, NMC, LFP, ECPs
Anode	Graphitic carbons, Hard carbons, Synthetic graphite, LTO, Tin-based alloys, Silicon-based alloys
Electrolyte salts	$LiPF_6$, $LiClO_4$, $LiAsF_6$, $LiCF_3SO_3$, $LiBF_4$
Electrolyte solvents	DMC, EC, DEC, PC, ɣ-GBL, RTIL's
Flame retardants	HMPN, TMP, TFP
Gel precursor	PEO, PAN, PVDF, PMMA, PTFE
Binder	PVDF, SBR, Glass Fibre, CMC, ACM
Separator	Polypropylene, Polyethylene, Cellulosic paper, Nonwoven fabrics, Ceramic

LMO: Lithium Manganese Oxide, LCO: Lithium Cobalt Oxide, NCA: Lithium Nickel Cobalt Aluminium Oxide, NMC: Lithium Nickel Manganese Cobalt Oxide, LFP: Lithium Iron Phosphate, ECPs: Electronic Conducting Polymers, LTO: Lithium Titanate, PVDF: Polyvinylidene Fluoride, SBR: Styrene Butadiene Rubber, CMC: Carboxymethyl Cellulose, ACM: acrylate-type copolymer, RTIL's: Room Temperature Ionic Liquids, DMC: Dimethyl Carbonate, EC: Ethylene Carbonate, DEC: Diethyl Carbonate, PC: Propylene Carbonate, ɣ-GBL: gamma-Butyrolactone, HMPN: hexamethoxycyclotriphosphazene, TMP: trimethyl phosphate, TFP: tris(2,2,2-trifluoroethyl)phosphate, PEO: Polyethylene Oxide, PAN: Polyacrylonitrile, PMMA: Poly Methyl Methacrylate, PTFE: Polytetrafluoroethylene.

2. Safety issues and challenges related to lithium ion batteries

2.1. Battery materials and components

LIBs are rechargeable energy storage devices where Li ions move between the anode and cathode, which are electrically separated by a membrane. All components are fully soaked in an electrolyte. During charging, lithium ions move from the cathode towards the anode and in the discharge cycle the ions travel back. The electrons move via the external electrical circuit and lithium ions and solvent molecules travel within the electrolyte. When the battery is charged, the Solid Electrolyte Interface (SEI) is formed. This passivation layer, Li^+ conducting and electronically insulating, is paramount for optimum battery performance as it allows Li intercalation and prevents further electrolyte decomposition [26,27].

As the risks associated with a certain battery technology depend highly on the cell constituents, it is important to consider all relevant components from a safety perspective. Table 1 summarizes typical components found in LIBs. A relatively high number of materials have been used in cathodes, including lithium manganese oxide (LMO), lithium cobalt oxide (LCO), lithium nickel cobalt aluminium oxide (NCA), lithium nickel manganese cobalt oxide (NMC) or olivine type materials, such as lithium iron phosphate (LFP). The latter has appeared as one of the safest chemistries due to its thermal stability and non-toxicity [28,29]. On the other hand the energy density in LFP batteries is lower compared to LCO alternatives, which have less desirable behaviour when a thermal event occurs [30,31].

Regarding the anode, carbon is commonly used in LIBs. It can reversibly accommodate significant amounts of lithium providing a theoretical capacity of $372\ mA\,h\,g^{-1}$ (LiC_6). More recently, lithium titanate (LTO) has attracted considerable attention due to its long cycle life without significant structural changes upon cycling [32,33] and its increased safety in terms of thermal stability and high potential which prevents dendrite formation [30] at the cost of a comparatively lower voltage [30].

Electrolytes used in LIBs are mainly based on aprotic organic solvents, often highly flammable [34]. The most commonly used electrolytes are mixtures of various carbonates (e.g. propylene carbonate) and a dissolved salt (e.g. lithium hexafluorophosphate ($LiPF_6$)). In the event of thermal runaway, the electrolyte decomposes leading to the formation of gases. Consequently, significant overpressure is generated in the cell, which will eventually lead to venting and/or rupture. A major hazard is the presence of fluorinated compounds in the electrolyte, leading to the release of toxic and corrosive hydrogen fluoride (HF). Since some gases generated in such events are toxic [35,36] and may potentially cause severe harm to individuals in the surroundings, immediate medical attention is required after exposure to vented gases [16]. In order to reduce the flammability of these electrolytes various flame retardant additives have been explored giving rise to the concept of “non-flammable electrolytes” (e.g. Phosphate solvents [37], phosphazene derivatives [38,39], room temperature ionic liquids [40,41]). Safety performance of LIBs can be improved using alternative electrolytes such as more thermally stable, high flashpoint electrolytes [42] or room temperature ionic liquids (RTILs) [40,41], which show promise due to their low volatility, with virtually no vapour pressure (ca. 100 pPa at 298 K for 1-butyl-3-methylimidazolium hexafluorophosphate [43] compared with 3 kPa at 298 K for H_2O [44]), high flame resistance, thermal and chemical stability together with a wide window of electrochemical stability [45]. Electrolytes in the solid/gel form (solid polymer electrolytes), can also be utilized. On one hand their ionic conductivity is much lower than in liquid systems, but on the other hand their safety is improved (e.g. lower reactivity versus lithium, absence of risk of electrolyte release) [46,47].

The binder is essential for enabling electrode fabrication. Initially, most of the anodes were obtained by utilizing polyvinylidene fluoride (PVDF), however the current trend is to use styrene butadiene rubber (SBR), which yields more flexible electrodes, higher binding ability with a small amount of binder, larger battery capacity and higher cyclability [48]. SBR is unsuitable for the cathodes, which are prone to oxidation and consequently PVDF is still used. Electrode preparation with PVDF requires N-methyl pyrrolidone (NMP) for dissolution with a consequent toxicity concern. Water - soluble binders (e.g. carboxymethyl cellulose, CMC) are preferred from an environmental perspective. More recently, the highly flexible acrylate-type copolymer (ACM) has started to be used in some prismatic batteries [48].

The separator is a key element for preventing the electrical contact between electrodes while allowing ion transport [49]. Currently, thin microporous polyolefin membranes made of polyethylene (PE), polypropylene (PP), or laminates of both (e.g. PP/PE/PP [50]) are mostly used. In a hazardous situation when a temperature above the melting point of PE is reached (135 °C), PE will melt, whereas PP (melting point of 165 °C) will maintain its integrity. As the polymer melts, its pores are blocked resulting in an insulating layer, effectively shutting down the cell and providing a degree of protection against short circuit and overcharge [49]. Alternatively separators based on ceramic materials have also shown high-temperature stability, good chemical resistance, and wettability [51].

It is clear that many aspects influence the safety of LIBs and the evaluation of all battery design parameters (e.g. electrode material, particle size [52], separator) is needed in order to optimise safety. Furthermore, in order to achieve a safe system for a particular application a compromise in the selection of cell components with respect to safety, performance and cost is essential.

2.2. Battery cell and pack design

Industry experts estimate that between one in 10 million [11] or one in 40 million [34] cells fail during normal operation, if proper quality control is in place. Despite the low probability, the risk is not trivial and the consequences cannot be neglected. For this reason, efforts to improve the safety of the batteries are taken along the whole electric vehicle manufacturing chain [31], from safer components (see Section 2.1), smarter energy management [53] and battery management systems (BMS), and smarter vehicle designs (e.g. installation of battery pack away from crush zones [31] and other safety related installation considerations [54]. An additional parameter influencing battery safety is cell design [16]). Vehicle manufacturers utilize prismatic (e.g. VW, Audi, Porsche, Citroen, Peugeot, Fiat), pouch (e.g. Mini, Mercedes, Renault) or cylindrical cells (e.g. Tesla). Cylindrical cells are cheap to manufacture, have good mechanical stability and high energy density. However, they have low packing efficiency [55]. They do not swell during operation, but when pressure builds up expulsion of the jelly roll (layers of anode/separator/cathode rolled up and inserted into a hollow cylinder casing) can occur [56]. Prismatic cells are mechanically robust with high packing efficiency, however, they have slightly lower energy density and are more expensive [55]. In case of pressure build up, the generated gases are released via the safety vent. When the opening of the safety vent is too small, or when it is clogged it can hinder the escape of gas. This situation can lead to rupture or explosion of the cell [16]. Soft pouch cells have a higher energy density than the other two designs, their fabrication cost is not very high, and they are much lighter. However, at system level this can be reversed due to the stronger mechanical constructions needed for their protection. They are prone to swelling during operation (e.g. ageing, exposure to > 60 °C [56]) and have no designated venting mechanism. In case of venting, gases are not directed towards a safety valve, as all the sealing points in the pouch cell impose small resistance to high pressure. Consequently, the release of gases occurs with smaller energy than for the other assemblies. The unconstrained nature of the pouch cells may be more effective preventing a thermal runaway reaction compared to cell designs where electrodes are forced to maintain close contact [57]. Additionally, pouch cells exhibit smaller internal temperature gradients compared to prismatic assemblies [55].

Another aspect associated to battery safety relates to the fact that cells within a pack exhibit non-uniform properties upon cycling. Consequently, there may be some unbalances (e.g. voltage variations between cells) that may trigger a safety hazard.

Battery ageing also needs to be evaluated. Battery cells degrade both by undergoing charge-discharge cycles and by time (calendar ageing). The application and safety of “second life” automotive batteries should be considered. In this application, decommissioned vehicle traction batteries may be used for stationary storage (e.g. electric grid support).

A final relevant aspect is the design of the battery pack. For example, standards such as SAE J2289:2008 [58] describe that material vented from the battery should not be directed into the passenger compartment where it may pose a hazard to passengers.

3. Relevant standards and regulations: abuse testing of lithium ion batteries for automotive applications

Lithium ion batteries must pass a series of safety tests to be certified for use in a particular application (e.g. portable electronics or automotive). Safety tests are described in international, national and regional standards, typically developed based upon pre-normative research and experience from industry, academia and regulatory bodies. These tests are performed to understand and identify potential battery weak points and vulnerabilities when the battery experiences real-life off-normal conditions and to determine how the battery will behave under severe abusive conditions, such as a car crash or thermal shock. In these situations, thermal runaway can develop. Other causes of a thermal runaway can be the presence of microscopic particles from manufacturing or impurities, which can pierce the separator creating an internal short circuit. Therefore, a thermal runaway can be initiated by both external and internal stimuli. The consequences that thermal runaway produces vary depending on several factors, including: state of charge (SOC), charging/discharging rate, cell-type, cell history, cathode/anode material, electrolyte composition, etc. [59].

Many tests presented in this review are devoted to the evaluation of the consequences of a short circuit, which might be followed by thermal

Table 2
Overview of tests in standards and regulations applicable to lithium ion batteries in automotive applications. Test level is indicated as C: Cell, M: Module, P: Pack and V: Vehicle.

	Region of applicability		International					EU and further countries[a]	USA			Korea	India	China
	Test	Section	SAE J2464 [61] (2009)	SAE J2929 [66] (2013)	ISO 12405-1 (2) [67,68][c] (2012)	ISO 12405-3 [69][c] (2014)	IEC 62660-2 (3) [70,71] (2011 (2016))	UN/ECE-R100.02 [62] (2013)	UL 2580 [63] (2013)	USABC [72] (1999)	FreedomCAR [65] (2005)	KMVSS 18-3 [73] (2009)	AIS-048 [74] (2009)	QC/T 743 [75][d] (2006)
Mechanical	Mechanical shock	3.1.a	C M P	C M P V	P	P	C	C M P V	C M[e] P	M P	M P		M	
	Drop	3.1.b	P	P					C P	P	P	P		C
	Penetration	3.1.c	C M P							C M P	C M P		C M	C P
	Immersion	3.1.d	M P	P		P			M P	M P	M P	P		
	Crush/crash	3.1.e	C M P	P V		P V	C	C M P V	C M P	C M P	C M P			C P
	Rollover	3.1.f	M P	P					P	M P	M P		M	
	Vibration	3.1.g		C M P	P	P	C	C M P	C M P	C M[e] P	C M P		M	P
Electrical	External short circuit	3.2.a	C M P	P	P	P	C	C M P	C M P	C M P	C M P	P	C M P	C P
	Internal short circuit	3.2.b					C							
	Overcharge/ overdischarge	3.2.c	C M P[f]	P	P	P	C	C M P V	C M P	C M P	M P	P	C M P[g]	C P
Environmental	Thermal stability	3.3.a	C				C		C	C M P	C M P	P		C P
	Thermal shock and cycling	3.3.b	C M P	C M P	P	P	C	C M P	C M P	C M P	C M P			
	Overheat	3.3.c	M P	P				C M P V		M P				
	Extreme cold temperature	3.3.d								C M P				
	Fire	3.3.e	M P	P		P V[b]		C M P V	C M P	C M P	C M P	P		
Chemical	Emissions	3.4.a	C M P	P					C M P	C M P	C M P			
	Flammability	3.4.b	C M P	P					C M P	C M P	C M P			

[a] Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.
[b] Vehicle body may be included,
[c] Also possible at battery pack subsystem: representative portion of the battery pack (energy storage device that includes cells or cell assemblies normally connected with cell electronics, voltage class B circuit, and overcurrent shut-off device, including electrical interconnections and interfaces for external systems,
[d] Applicable to the LIB cell and pack whose rated voltage is 3.6 V and nx3.6 V (n: quantity of batteries), respectively.
[e] At the module level for those electric energy storage assemblies intended for use in applications larger than passenger vehicles. The module level testing shall be representative of the electric energy storage assembly.
[f] Overdischarge not at pack level.
[g] Overdischarge not performed.

runaway, as this is one of the scenarios that may create a great risk, both for the vehicle occupants and first aid responders. In some tests the short circuit is induced externally, such as in the case of crush, penetration and drop tests, however other tests aim at inducing the short circuit internally. The development of tests representative of an internal short circuit is quite controversial due to the difficulty in emulating a true internal short circuit in a testing environment. For this reason, there is a lack of consensus regarding the "fit for purpose" of internal short circuit tests currently described in existing standards. There is little knowledge on how an internal short circuit within a battery pack develops. Most of the scientific literature refer to small batteries or cells [57,60], and analogous data at pack or full vehicle level is scarce due to the high cost of the tests and to the fact that the information is in most of the cases proprietary to the testing bodies or the OEM.

Table 2 presents a summary of the most frequently required abuse tests as described in international standards and regulations related to electric vehicles based on lithium ion technologies. Abuse tests are classified according to the nature of the misuse: mechanical, electrical, environmental and chemical. Tests that appear in only few standards or regulations will be mentioned but not explained in detail. In some circumstances, upon agreement between the manufacturer and the customer, the standard or regulation allows certain flexibility in the test conditions. The tests can be performed at various system levels: cell (C), module (M), pack (P) and vehicle (V). In general we will refer to the device under test (DUT). Definitions for each level follow SAE J2464:2009 [61] and can be summarized as:

- Cell (C): energy storage device composed of at least one cathode and one anode, and other necessary electrochemical and structural components.
- Module (M): grouping of interconnected cells in series and/or parallel into a single unit.
- Pack (P): interconnected modules including all auxiliary subsystems for mechanical support, thermal management and electronic control.

In general, standards and regulations set pass/fail requirements for each test. For example, UN/ECE-R100.02 [62], ISO 12405-3, UL 2580 [63] set "no fire", "no explosion", "no rupture", and "no leakage" as acceptance criteria for tests under reasonable foreseeable misuse (e.g. vibration, thermal shock, external short circuit), whereas the pass/fail criterion for fire resistance is "no explosion" only. Specific to automotive applications, the response of a technology to an abusive condition can be classified according to the EUCAR hazard levels [64,65]: from level 0 (no effect, system maintains its functionality) to level 7 (explosion, mechanical disintegration of the system). Battery and car manufacturers often utilize this classification to evaluate the response of a RESS to an abusive condition. For example, a level 3 or lower usually represents an acceptable level of performance.

Direct comparison of the value of each testing parameters should be performed prudently. Differences in test parameters may be rationalised by differences in the scope and purpose of the tests. For particular tests of interest the reader is advised to consult the reference texts directly.

3.1. Mechanical tests

3.1.1. Mechanical shock test

The mechanical shock test aims at evaluating the robustness of a battery in situation of sudden acceleration and/or deceleration of a vehicle. During the test a DUT is exposed to shock forces defined in terms of acceleration and shock duration adapted to different conditions; from normal in-use driving, driving at high speed over a kerbstone [67], to vehicle crash [62,65,72]. There is a great diversity in the test conditions (direction, peak acceleration, duration, state of charge) in the various standards and regulations, as summarized in Table 3. To facilitate the comparison between the various parameters please refer to Fig. 1. Standards SAE J2464:2009 and SAE J2929:2013 [61,66] follow UN 38.3:2015 transportation regulation [76], and require the most stringent conditions of all the standards and regulations evaluated, in terms of peak acceleration (150g) for cells of < 0.5 kg. For heavier systems the conditions are eased [61,66].

Interestingly, ISO 12405 part 1:2011 and part 2:2012 [67,68], UL 2580:2013 [63] and ISO 62660-2:2011 [70] (which follow ISO 16750-3:2003 [77]) have the same requirements (500 m s^{-2} (~ 51 g) and 6 ms) despite the fact that the test levels are different (P, P, C and C, respectively, see Table 3). It is reasonable to assume that the impact and outcome of the test is dependent on the DUT size, and that the test conditions should be dimensioned to each level.

Under the recently published ISO 12405-3:2014 [69], an optional mechanical shock test is included compared to parts 1 and 2 [67,68], adopting the shock parameters used by UN/ECE-R100.02:2013 [62]. This regulation specifies test parameters for batteries to be installed in road vehicles of categories M_1-N_1, M_2-N_2 and M_3-N_3[1] with varying acceleration profiles depending on orientation and vehicle type. A higher shock level and/or longer duration can be applied to the DUT if recommended by the manufacturer.

FreedomCAR and USABC standards [65,72] divide the shock test into low-level (no damage to the DUT) and mid-level (DUT may be inoperable after test). While all considered standards and regulations require a half-sine wave, FreedomCAR and USABC allow also other pulse shapes which would simulate actual decelerations more accurately. Also deviations from the specified shock parameters may be requested by the manufacturer. These two standards [65,72], as well as UN/ECE-R100.02:2013 [62], present significantly higher shock durations (ranging 55–120 ms) compared to the other standards (< 20 ms), presumably imposing harder conditions on the DUT.

Mechanical shock testing can also be performed at vehicle level, as mentioned in UN/ECE-R100.02:2013 [62], SAE J2929:2013 [66] and ISO 12405-3:2014 [69]. For UN/ECE-R100.02:2013 [62], batteries installed in a vehicle that has already been successfully subjected to vehicle crash testing in accordance with UN/ECE-R12:2012 – Annex 3 [78] for protection of the driver against the steering mechanism in the event of impact, with UN/ECE-R94:2012 – Annex 3 for frontal collision [79] and with UN/ECE-R95:2011 – Annex 4 for lateral collision [80] are considered to be compliant. SAE J2929:2013 [66] follows requirements described in FMVSS 305:2011 [81] (or equivalent regulation depending on the geographical region applicable to vehicle front, rear and side crash testing). Similarly ISO 12405-3:2014 [69] requires following relevant national or regional regulations on vehicle crash tests.

According to the FP7 project EVERSAFE [82], the majority of real world crashes show acceleration values below 20–30g for frontal and side impacts with durations lower than 100 ms, and accelerations significantly lower (< 12g) in the case of rear impacts. However, when the aim of the test is to evaluate worst case scenarios, the parameters would need to be more stringent, particularly for standards and regulations investigating vehicle crash scenarios. For example, full-width barrier crash test (56 km h^{-1}) develops shock peaks up to 55g [83], only ISO 12405 part 1:2011 and part 2:2012 [67,68] approximate this value at pack level. Based on these examples, comparability of test conditions performed at vehicle level and component level would require deep evaluation. Another aspect pointed out by the project

[1] Vehicles designed for the carriage of passengers: (M_1: < 8 seats in addition to the driver's seat, M_2: > 8 seats in addition to the driver's seat, mass < 5 tonnes. e.g. small buses and minibuses, M_3: > 8 seats in addition to the driver's seat and a maximum mass > 5 tonnes. e.g. large buses) and vehicles designed and constructed for the carriage of goods: (N_1: having a maximum mass < 3.5 tonnes. e.g. light vans and trucks, N_2: having a mass between 3.5 and 12 tonnes e.g. mid-sized vans and trucks, and N_3: exceeding 12 tonnes. e.g. heavy vans and trucks).

Table 3
Test conditions for the mechanical shock test at cell (C), module (M), pack (P) and vehicle (V) level.

Region of applicability	International					EU and further countries[#]	USA			Korea	India	China
Shock parameters	**SAE J2464** [61]	**SAE J2929** [66]	**ISO 12405-1(2)** [67,68]*	**ISO 12405-3** [69]*	**IEC 62660-2(3)** [70,71]**	**UN/ECE-R100.02** [62][##]	**UL 2580** [63]	**USABC** [72]***	**Freedom CAR** [65]***	**KMVSS 18-3** [73]	**AIS-048** [74]	**QC/T 743** [75]
Level (C, M, P)	C M P	C M P	P	P	C	C M P	C M^{+} P	M P			M	
Direction of shock	Positive and negative directions. 3 repeats on 3 axes (total 18 shocks)	Positive and negative directions. L and lateral axes	###	### L and T	###	L and T	### (C), Positive and negative directions. 3 repeats on 3 axes (total 18 shocks) (M, P)	Axis that will cause the most potential damage			V and H axis	
Peak acceleration (g)	150 (C), 50 (C > 0.5 kg M,P > 12 kg) or 25 (P)	150 (C M P), 50 (C > 0.5 kg M,P > 12 kg) or 25 (P)	51	51 or Vehicles ≤ 3,5 t: 10–28 (L)//4.5–15 (T), Medium-duty trucks and midi buses: 5–17 (L)//2.5–10 (T), Heavy-duty trucks and buses: 4–12 (L)//2.5–10 (T)	51	Vehicles ≤ 3,5 t: 10–28 (L)//4.5–15 (T), Medium-duty trucks and midi buses: 5–17 (L)//2.5–10 (T), Heavy-duty trucks and buses: 4–12 (L)//2.5–10 (T)	51 (C) 25 (M, P)	30 (mid-1) 20 (mid-2) 20 (low)			30	
Shock duration (ms)	6 (C) 11 (C > 0.5 kg M,P > 12 kg) or 15 (P)	6 (C M P) 11 (C > 0.5 kg M,P > 12 kg) or 15 (P)	6	6 or 80–120	6	80–120	6 (C) 15 (M, P)	≤ 55 (low) ≤ 65 (mid-1) ≤ 110 (mid-2)			15	
SOC (% rated capacity)	95-100	95–100% max. normal vehicle operation	50	50 or > 50% normal operating range	80 (HEV), 100 (BEV)	> 50% normal operating range	Max. operating SOC (M, P), 80 (HEV), 100 (BEV) (C)	100			100	
Vehicle level (V)/collision speed		FMVSS 305 [81]: 48, 54, 80 km h^{-1}		Relevant national or regional regulation on vehicle crash tests		UN/ECE-R95 [80]: 48.3-53 km h^{-1}, UN/ECE-R94 [79]: 56 km h^{-1}, UN/ECE-R12 [78]: 50 km h^{-1}						

Longitudinal (L), transversal (T), vertical (V), horizontal (H), * or according to a test profile determined by the customer and verified to the vehicle application. ** If more severe test parameters are requested by any regulation, such test conditions may be applied. *** It is in the interest of DUT manufacturers to keep the pulse duration as long as possible and still meet the specification. However, if the electrochemical storage system (ECSS) is robust, tests may exceed the peak acceleration, reduce the duration, reduce the test complexity, and hence, reduce the test cost. [#]Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia. [##] A higher shock level and/or longer duration can be applied to the tested-device if recommended by the manufacturer. [###] Same direction as the acceleration of the shock that occurs in the vehicle. If the direction of the effect is not known, the cell shall be tested in all six spatial directions. [+] For those electric energy storage assemblies intended for use in applications larger than passenger vehicles. The module level testing shall be representative of the electric energy storage assembly.

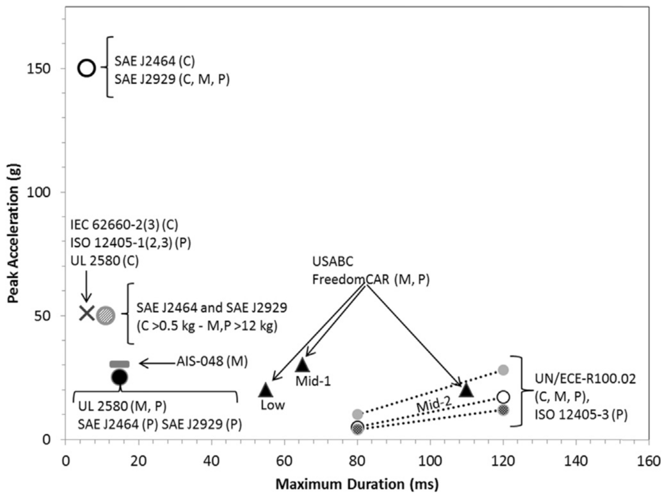

Fig. 1. Comparison of peak acceleration and shock duration for various standards and regulations.

EVERSAFE [82] is that the shock parameters defined in the standards and regulations are extracted from conventional car testing, however the accelerations experienced by the battery in the vehicle installation might be different for EVs. Investigations in this respect would be highly desirable to evaluate whether specific requirements for electric vehicles need to be imposed.

3.1.2. Drop test

This test simulates a situation when a battery is being removed from or installed in an electric vehicle and accidentally drops. Table 4 shows the requirements for surface type, drop height and SOC. During the test the DUT is let fall onto a rigid flat surface (e.g. concrete floor [63,73]) or onto a cylindrical object made of steel [65,72]. The shape of this cylindrical object is supposed to represent a telephone pole or a similar object. Alternatively, it is also possible to perform a horizontal impact of equivalent velocity as described in SAE J2464:2009 [61] or USABC:1999 [72]. The fall height varies considerably in the various standards (from 1 m [63] up to 10 m [65,72]). Consequently, the outcome of the test can be expected to vary.

Systems intended to be removed from the vehicle for charging (or replacement/swapping) are required to perform this test in UL 2580:2013 [63]. In this case, the test has to be repeated three times (on the same item) as the likelihood of dropping the battery is higher than if the battery does not need to be removed from the vehicle. This scenario seems very plausible, however, the drop test is not included in various automotive battery regulations and standards, such as UN/ECE-R100.02:2013 [62], ISO 12405-1: 2011, ISO 12405-2:2012, ISO 12405-3:2014 [67–69] and ISO 62660-2:2011 [70].

3.1.3. Penetration test

In this test, both mechanical and electrical damage is induced in the battery. A sharp steel rod – the 'nail' – is forced through the battery at a certain constant speed, generally 8 cm s^{-1} [65,72,74]. Although the consequence of the test is a short circuit, this short circuit is mechanically induced. For this reason, the penetration test is usually classified within the mechanical tests and not within electrical tests. As the nail penetrates through the cells and the integrity of the separator and electrodes is compromised, short circuits are created and consequently heat is released. Multiple electrode layers are in electrical contact, together with the shorting occurring on the nail, so relatively important damage occurs in a short period of time. Additionally, due to the fact that the deformation is localized in a relatively small area, the heat dissipation is quite limited.

Depending on the test level (cell, module or pack), the depth of penetration and the dimension of the nail vary as described in many of

Table 4
Test conditions for the drop test at cell (C), module (M) and pack (P) level.

Region of applicability	International				EU and further countries[#]	USA			Korea	India	China
Drop parameters	SAE J2464 [61]	SAE J2929 [66]	ISO 12405-1 (2)(3) [67–69]	IEC 62660-2 (3) [70,71]	UN/ECE-R100.02 [62]	UL 2580 [63]	USABC [72]	FreedomCAR [65]	KMVSS 18-3 [73]	AIS-048 [74]	QC/T 743 [75]
Level (C, M, P)	P	P				C P	P	C M P	P		C
Surface type		Flat surface				Flat concrete surface[a]	Cylindrical steel object (radius 150 mm)		Concrete floor		Hardwood floor 20 mm thick
Drop height (m)	2	maximum distance to ground or maximum possible drop distance which the battery system experiences when serviced according to documented procedures or ≥ 1				1	10	≤ 10	4.9		1.5
SOC (% rated capacity)	95–100	95–100% max. normal vehicle operation				Max. operating SOC		100	Max. operating range of a vehicle or 80% SOC		100

[#]Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.
[a] If only one drop test is performed, it shall not be a flat drop. If the electric energy storage assembly is intended to be installed or removed in a horizontal direction, a drop with the DUT slanted at a 10° angle with pack edge impacted, should be considered.

Table 5
Test conditions for the penetration test at cell (C), module (M) and pack (P) level.

<table>
<tr><th>Region of applicability</th><th colspan="4">International</th><th>EU and further countries#</th><th colspan="3">USA</th><th>Korea</th><th>India</th><th>China</th></tr>
<tr><th>Penetration parameters</th><th>SAE J2464 [61]</th><th>SAE J2929 [66]</th><th>ISO 12405-1 (2)(3) [67–69]</th><th>IEC 62660-2 (3) [70,71]</th><th>UN/ECE-R100.02 [62]</th><th>UL 2580 [63]</th><th>USABC [72]</th><th>Freedom CAR [65]</th><th>KMVSS 18-3 [73]</th><th>AIS-048 [74]</th><th>QC/T 743 [75]</th></tr>
<tr><td>Level (C, M, P)</td><td>C M P</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">C M P</td><td></td><td>C M</td><td>C P</td></tr>
<tr><td>Speed (cm s^{−1})</td><td>≥ 8</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">8</td><td></td><td>8</td><td>1–4</td></tr>
<tr><td>Diameter of Rod (mm)</td><td>3 (C) 20 (M, P)</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">3 (C) 20 (M, P)</td><td></td><td>3 (C) 20 (M)</td><td>3–8</td></tr>
<tr><td>Minimum Depth of Penetration</td><td>Cell (C) 3 cells or 100 mm (M, P)</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Cell (C) 3 cells or 100 mm (M, P)</td><td></td><td>Cell (C) 3 cells or 100 mm (M)</td><td>Not specified (C) 3 cells (M, P)</td></tr>
<tr><td>SOC (% rated capacity)</td><td>95–100</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">100</td><td></td><td></td><td>100</td></tr>
</table>

#Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.

the standards (see Table 5). In most cases, a 3 mm diameter rod is required at cell level and a 20 mm diameter rod is required at module or pack level. The depth of penetration is at least through the entire cell for cell level testing and through cells or 100 mm (whichever is greater) for module or pack testing [61,65,72,74,75]. In all cases the rod remains in place during the post-test observation period (e.g. 1 h). For FreedomCAR:2005 [65] this is not explicitly mentioned.

The usefulness of this test is questioned by many in the research community [57,84], for three main reasons: first the test is not fully representative of an event that would likely occur in a real - situation (e.g. a sharp object penetrating inside the battery compartment within a vehicle), second it has been proven that the test does not represent a spontaneous internal short circuit [57,85,86] and finally there are many parameters that can strongly affect the outcome of the test, for example: nail speed, nail dimension and SOC of the battery [60,87,88]. Furthermore, it is uncertain as to the influence the quality and composition of the nail material may have on the outcome of the test and standards and regulations do not provide guidance on this. For all the reasons mentioned above it seems comprehensible that this test is not included in many of the automotive standards and regulations as displayed in Table 5.

3.1.4. Immersion test

The immersion test has been developed to simulate a situation where a battery is submerged or where battery assemblies installed in the underbody of the vehicle are partially flooded. In order to perform this test, the (fully charged) battery is completely submerged in salt water with a composition similar to seawater (e.g. 5 wt% NaCl (aq.)) at 25 °C for a period of at least 1–2 h or until any visible effects (e.g. bubbling) have stopped [61,63,65,66,72,73] (see Table 6). The immersion into other liquids, such as engine coolant or fuel, is also recommended in FreedomCAR:2005 [65].

In the latest version of ISO 12405, part 3 published in 2014 [69], the water immersion test is newly introduced (not included in parts 1 and 2 [67,68]). Unfortunately, the test is not described in much detail and it is merely pointing out that the consequence of the test is a short circuit with hazardous gases possibly being released.

It is important to evaluate the frequency or likelihood of an electric vehicle exposed to a flood situation. For example in the Netherlands around 700–800 car accidents per year result in vehicles flooded in a ditch or canal [89]. Around 1200 to 1500 vehicles end up submerged in water in the United States every year [90]. Additionally, there are quite frequent situations where hurricanes or storms cause numerous vehicles to be submerged. Just to mention some examples, up to 250,000 cars were destroyed in Hurricane Sandy in 2012 [91] and several incidents involving EVs occurred (e.g. 16 submerged Fisker Karma's in Hurricane Sandy leading to fire [92]). Another example where moisture led to a fire event was the BAE Systems HybriDrive incident [93]. Based on these incidents, it seems that the performance of the test would be of relevance, however many of the standards and regulations do not include this test (see Table 6).

3.1.5. Crush/crash test

In this test, the applied crush force emulates a vehicle accident or any external load force that may damage the battery enclosure and cause its deformation. In the crush test, also referred to as battery enclosure integrity test [66], an electrically insulated plate usually textured or ribbed [62,65,72] is pressed down onto the battery until a certain compression is reached (e.g. crush to 85% of initial dimension and after 5 min continue crushing up to 50% of initial dimension [61,65,72,75]) or until an abrupt voltage drop is observed (e.g. reduction by 1/3 of original cell voltage [70]). Two standardized crush surfaces are normally used, type A and type B whose characteristics and dimensions are displayed in Fig. 2. Typically, for cell level testing (cylindrical or prismatic), type B crushing bar (as described in IEC 62660-2:2011 [70]) is used. For module or pack assemblies crushing plate type A is generally recommended.

Table 6
Test conditions for the immersion test at cell (C), module (M) and pack (P) level.

Region of applicability	International					EU and further countries#	USA			Korea	India	China
Immersion parameters	SAE J2464 [61]	SAE J2929 [66]	ISO 12405-1 (2) [67,68]	ISO 12405-3 [69]	IEC 62660-2 (3) [70,71]	UN/ECE-R100.02 [62]	UL 2580 [63]	USABC [72]	FreedomCAR [65]	KMVSS 18-3 [73]	AIS-048 [74]	QC/T 743 [75]
Level (C, M, P)	M P	P		P			M P	M P	C M P	P		
Immersion Fluid	5 wt% NaCl			Clear or salty water			5 wt% NaCl	Nominal composition of sea water		0.6 M NaCl		
Temperature (°C)	25 ± 5			25 ± 2			25 ± 5	25	25 ± 2 ± 5% of reading	25 ± 5		
Immersion time	≥ 2 h or until any visible reactions have stopped			Not specified			> 1 h or until any visible reactions have stopped	≥ 2 h or until any visible reactions have stopped		1 h		
SOC (% rated capacity)	95–100			> 50% normal operating range (HP) Max. SOC at normal operation (HE)			Max. operating SOC		100	Max. operating range of a vehicle or 80% SOC		

HP: High power applications. HE: high energy applications.
#Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.

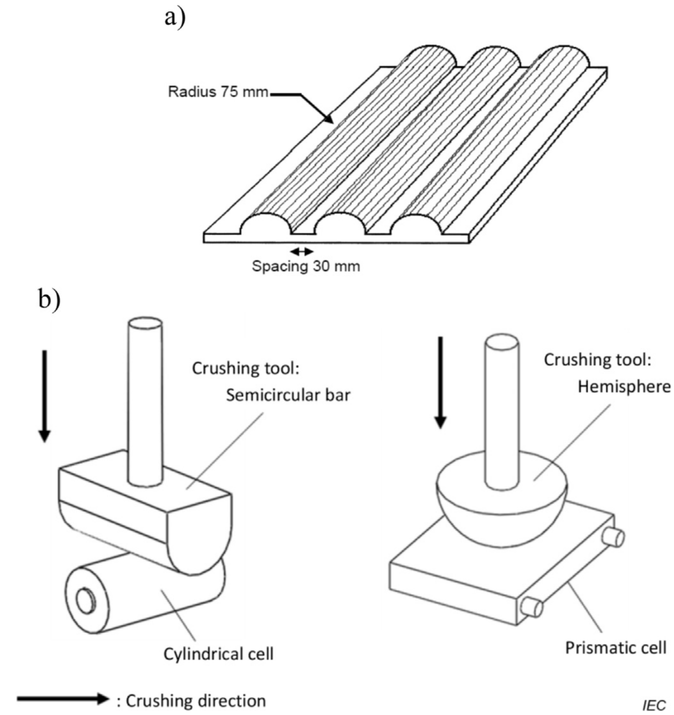

Fig. 2. Crushing plate a) type A and b) type B. Reprint from IEC 62660-2 ed.1.0 Copyright © 2010 IEC Geneva, Switzerland. www.iec.ch.[3] [3] "The author thanks the International Electrotechnical Commission (IEC) for permission to reproduce Information from its International Standard IEC 62660-2 ed.1.0 (2010). All such extracts are copyright of IEC, Geneva, Switzerland. All rights reserved. Further information on the IEC is available from www.iec.ch. IEC has no responsibility for the placement and context in which the extracts and contents are reproduced by the author, nor is IEC in any way responsible for the other content or accuracy therein".

Guidance on crush plate position is missing in most of the cases. SAE J2464:2009 [61] requires the test to be performed at the most vulnerable location to include the main cell area, whereas UN/ECE-R100.02:2013 [62] allows the manufacturer together with the technical service (e.g. certified testing body) to decide the plate position taking into consideration the direction of the travel of the DUT relative to its installation in the vehicle.

Some standards indicate that the force to be applied in the crush test has to be limited to 1000 times the weight of the battery [61,65,70,72] whereas others have a fixed force (e.g. 100 kN [62,63,66]) (Table 7), independent of the size of the battery to be tested. The implementation of the first option might lead to some issues testing traction batteries. As pointed out by Wech et. al. [94] maximum forces of less than 1000 times the battery weight might not be sufficient to achieve the required compression (e.g. 50% of battery dimension [61,65,72,75]). This would be the case for pack level testing following USABC:1999 [72], FreedomCAR:2005 [65] and SAE J2464:2009 [61]. For example, in the case of the small battery (24 kg, 0.8 kW h) of the Mercedes-Benz S400 HYBRID , only 11% deformation would be achievable [94]. Applying this requirement to a full HEV battery pack with 1.5–3 kW h, or to an EV battery pack with 15–35 kW h, having weights ranging from 50 to 200 kg, would require a minimal load of 500–2000 kN. This is an unrealistic scenario, as maximum loads rarely exceed 200 kN based on crash test simulations [94].

Another aspect that can raise some concern is the comparability of results between tests performed at component and vehicle level. Investigations of real world accident scenarios on occurrence of deformations in selected positions of the vehicle, together with simulations on fuel cell vehicles equipped with a compressed hydrogen storage system lead to the conclusion that maximum contact loads are usually < 100 kN [95]. Applied crush force on the DUT at component and vehicle level might not be comparable as in the latter case the battery has extra

Table 7
Test conditions for the crush test at cell (C), module (M) pack (P) and for the crash test at vehicle (V) level.

Region of applicability	International					EU and further countries[#]	USA			Korea	India	China
Crush parameters	**SAE J2464** [61]	**SAE J2929** [66]	**ISO 12405-1 (2)** [67,68]	**ISO 12405 (3)** [69]	**IEC 62660-2 (3)** [70,71]	**UN/ECE-R100.02** [62]	**UL 2580** [63]	**USABC** [72]	**FreedomCAR** [65]	**KMVSS18-3** [73]	**AIS-048** [74]	**QC/T 743** [75]
Level (C, M, P)	C M P	P		P	C	C M P	C M P	C M P	C M P			C P
Crush speed (mm min^{-1})	0.5–1 (C) 5–10 (M, P)	5–10					5 – 10 (M, P)					
Crush force	≤ 1000 DUT weight	100 kN or expected intrusion as per FMVSS 305 [81]*		100–105 kN**	≤ 1000 DUT weight	100–105 kN***	≤ 1000 DUT weight (C) 100 ± 6 kN (M, P)	≤ 1000 DUT weight				
Crush plate type	B (cylindrical C) Parallel to crush surface (prismatic and pouch C) A (M, P)	A		A	B	A (≤ 600 mm × 600 mm)	B (C) A (M, P)	A	Solid cylindrical impactor half the cell average diameter (C) A (M, P)			Crush area > 20 m^2 (C) A (30 mm × 150 mm) (P)
SOC (% rated capacity)	95–100	95–100% max. normal vehicle operation		> 50% normal. operating range (HP) Max. SOC at normal operation (HE)	80 (HEV) 100 (BEV)	> 50% normal operating range	80 (HEV) 100 (BEV) (C) Max. operating SOC (M, P)		100			100
Vehicle level (V)		FMVSS 305 [81] [##]		Relevant national or regional regulation on vehicle crash test		UN/ECE-R12 [78], UN/ECE-R 94 [79], UN/ECE-R 95 [80]						

* If due to battery packaging location, no battery enclosure deformation is expected, this requirement is presumed to be met. The responsible organisation shall be responsible to make and document this conclusion. ** or a value determined by the customer depending on expected forces in vehicle crash tests. These values shall be based on appropriate analysis, e.g. vehicle crash tests or vehicle crash simulations. ***A higher crush force, a longer onset time, a longer hold time, or a combination of these, may be applied at the request of the manufacturer. [##] or equivalent regionally applicable for vehicle front, rear and side crash conditions. [#]Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.

protection provided by the chassis and battery enclosure. Additionally, there could be some disagreement centred around the fact that real world accidents have a dynamic nature, that is the battery is moving towards the impact zone, which is different from component level tests where the crush plate moves towards a static battery. Various published investigations have shown discrepancies between current standards and regulations and dynamic crash tests, and hence the authors of these investigations recommend appropriate modifications to the tests included in the regulatory framework [94,96].

The crush test can also be performed at vehicle level, the so-called *Crash test*. Electric vehicles shall comply with the crash safety requirements as for conventional vehicles. In Europe, vehicles have to pass the tests defined by the UNECE: steering mechanism, front impact, and side impact tests from UN/ECE-R12:2012, UN/ECE-R94:2012 and UN/ECE-R95:2011 [78–80] as described in UN/ECE-R100.02:2013 [62]. In the USA, vehicles need to comply with the test defined in the Federal Motor Vehicle Safety Standards, such as frontal rigid barrier, a side moving deformable barrier, a rear rigid barrier and a rear deformable barrier according to FMVSS 305:2011 [81]. Following the crush test, a roll over test, is performed in some cases. This is the case for SAE J2929:2013 [66], described in Section 4.1.f (Table 7).

3.1.6. Rollover test

This test, also referred to as rotation test, simulates overturn of a vehicle that might occur in an accident. Comparison of the different test parameters is presented in Table 8. In order to perform the test, the battery pack or module is slowly rotated (e.g. 6° s^{-1}) for one complete revolution (360°) in order to evaluate the presence of any leak (e.g. battery electrolyte, coolant liquid) or venting. Then, the DUT is rotated in 90° increments for another full rotation staying at each position for one hour [61,63,65,72,74].

The rollover test is usually performed after crash tests such as described in FMVSS 305:2011 [81] or after a crush test as described in SAE J2929:2013 [66]. In relation to the Korean standards, rollover testing is not part of Article 18-3, discussed in this review, but part of Article 91 (fuel system). The need for this testing is supported by the fact that around 220,000 light motor vehicles sustain rollover crashes in the US annually, which accounts for almost a third of all highway vehicle occupant fatalities [97]. Despite this fact, the rollover test is not included in various relevant standards and regulations, such as UN/ECE-R100.02:2013 [62].

It is interesting to point out the discrepancy between standards with respect to the applicability of the rollover test for certain types of battery chemistry: while UL 2580:2013 [63] mentions specifically that flooded lead acid batteries are not subjected to this test, AIS-048:2009 [74], on the contrary, states that the test is applicable only for flooded lead acid batteries.

3.1.7. Vibration test

Although vibration occurs in any driving environment under normal operating conditions, because it may be considered abusive to the battery, almost all of the standards and regulations evaluated in this review include a vibration test. The purpose of this test is to evaluate the effect of long-term vibration profiles – representative of driving – on the battery, both in terms of the durability and in terms of identification of design flaws. The vibration profiles vary quite considerably over a wide range of frequencies and amplitudes (see Table 9). In order to facilitate the comparison of the various vibration parameters, Fig. 3a and b display the sine wave and random profiles used in the evaluated standards and regulations. Sine swept testing is commonly used to identify product resonances, while random vibration simulates everyday life scenarios that a DUT would experience [98,99].

The vibration profiles in standards and regulations are derived from generic measurements from conventional vehicles at locations appropriate for mounting traction batteries in EVs. In fact, there are

Table 8
Test conditions for the rollover test at module (M) and pack (P) level.

Region of applicability	**International**			**EU and further countries#**		**USA**			**Korea**	**India**	**China**
Rollover parameters	**SAE J2464** [61]	**SAE J2929** [66]	**ISO 12405-1 (2)(3)** [67–69]	**IEC 62660-2 (3)** [70,71]	**UN/ECE-R100.02** [62]	**UL 2580** [63][a]	**USABC** [72]	**FreedomCAR** [65]	**KMVSS 18-3** [73]	**AIS-048** [74][b]	**QC/T 743** [75]
Level (M, P)	M P	P				P		M P		M	
Rotation speed (continuous revolution)	360° min^{-1}					360° min^{-1} in 3 mutually perpendicular directions		360° min^{-1}		360° min^{-1}	
Rotation steps incremental revolution/hold time per increment	90° h^{-1}	90° (within 60–180 s)/5 min						90° h^{-1}		90° h^{-1}	
SOC (% rated capacity)	95–100	95–100% max. normal vehicle operation				Max. operating SOC		100			

#Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.
[a] Except for flooded lead acid batteries.
[b] Applicable only for flooded lead acid batteries.

Table 9
Test conditions for the vibration test at cell (C), module (M), pack (P) and vehicle (V) level.

Region of applicability	**International**					**EU and further countries[#]**	**USA**				**Korea**	**India**	**China**
Vibration parameters	**SAE J2464** [61]	**SAE J2929** [66][c]		**ISO 12405-1 (2)(3)** [67–69][c]	**IEC 62660-2 (3)** [70,71]	**UN/ECE-R100.02** [62]	**UL 2580** [63]		**USABC** [72]	**Freedom CAR** [65]	**KMVSS 18-3** [73]	**AIS-048** [74]	**QC/T 743** [75]
Level (C, M, P)		C M P		P	C	C M P	C	M[f] P	C M P			M	P
Type of profile		Random	Sine wave	Random	Random	Sine wave logarithmic sweep	Random		[g] or Sine wave or Random			Sine wave	Linear sweep
Frequency range (Hz)		10–190[a]	7–200[d]	5–200[e]	10–2000[e]	7–50[b]	10–2000[e]	10–190[a]	10–190[a]			30–150	10–55
PSD wave random $(m\ s^{-2})^2/Hz$		0.4–11[a]		0.02–5.8[e]	0.14–20[e]		0.14–20[e]	0.4–11[a]	0.4–11[a]				
Loading range sine wave $(m\ s^{-2})$			9.81–19.6 (> 12 kg)[d] 9.81–78.5 (< 12 kg)[d]			2–10[b]			7–49			30	30
Axis		Vertical, longitudinal, lateral	Three mutually perpendicular mounting positions of the cell	Vertical, longitudinal, transversal		Vertical	Vertical, longitudinal, lateral					Vertical axis and horizontal	Vertical
SOC (% rated capacity)		95–100% max. normal vehicle operation		50	80 (HEV) 100 (BEV)	> 50% normal operating range	80 (HEV) 100 (BEV)	100 & 20 (Z-sine, random) 60 (X & Y-sine, random)	100 & 20 (Z-sine, random) 60 (X & Y-sine, random)			100	
Vehicle level (V)		SOC at normal vehicle operation											

PSD: Power spectral density
[#]Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.
[a] Based on SAE J2380:2009 [102].
[b] Higher can be requested by manufacturer.
[c] A profile 'which reflects the application' may be used as alternative.
[d] Based on UN 38.3:2015 [76].
[e] Based on IEC 60068-2-64:1993 [101].
[f] At the module level for those electric energy storage assemblies intended for use in applications larger than passenger vehicles. The module level testing shall be representative of the electric energy storage assembly.
[g] Vibration endurance test in accordance with the anticipated end application vehicle vibration profile.

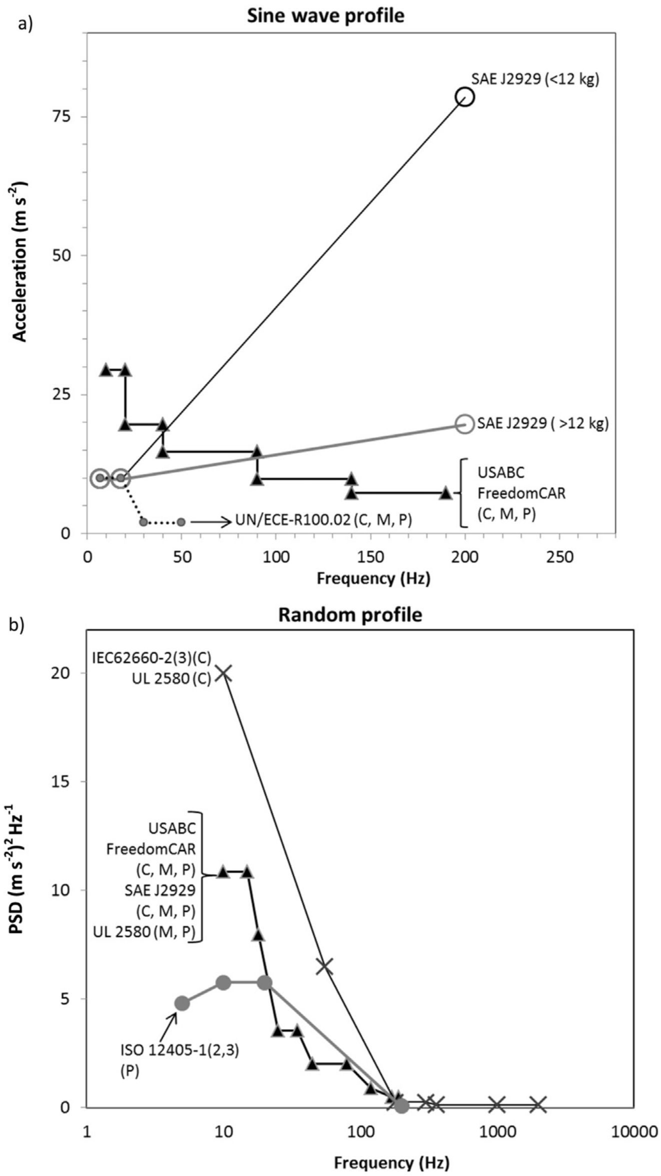

Fig. 3. Vibration profiles for the various standards and regulations requiring: a) sine wave profile and b) random profile.

very few works published on vibration profiles designed specifically to EVs and HEVs. Work published by Hooper et. al. pointed out that many of the vibration profiles described in the standards represent a short term abuse rather than a mechanical durability test to represent a battery life. Additionally it is suggested that battery packs may be exposed to vibration loads outside the range evaluated in existing standards [100].

Vibration test profiles in standards are adapted in most cases from UN 38.3:2015 [76], IEC 60068-2-64:1993 [101] or SAE J2380:2009 [102]. The vibration profile described in UN 38.3:2015 replicates vibrations during transport. This test is not considered relevant for the evaluation of battery resilience to vibration during driving conditions, since test conditions are not representative of the position of the battery and its fixture in the vehicle. For this reason the transport regulation is not discussed in detail in this review. Despite this, UN 38.3:2015 testing is provided as an alternative within SAE J2929:2013. On the other hand, standard IEC 60068-2-64:1993 [101] has been taken as the basis for IEC 62660-2(3):2011(2013): [70,71], ISO 12405-1(2):2011(2012) [67,68] and UL 2580:2013 [63]. It defines different test conditions for battery pack testing (up to 200 Hz) and for the electronic devices of the battery pack (cell level testing, up to 2000 Hz) due to the difference in mass of the DUT.

Lastly, SAE J2380:2009 [102] is also widely used to define random vibration profiles. Actually this standard is the basis for SAE J2929:2013 [66], UL 2580:2013 [63] (module and pack level only), USABC:1999 [72] and related FreedomCAR:2005 [65] standards and it reflects rough-road measurements at locations where traction batteries are likely to be installed in EVs/HEVs, equivalent to 100,000 miles usage.

Interestingly, ISO 12405 part 1 and 2 [67,68] are to our knowledge the only standards, that require vibration testing at different ambient temperature conditions, namely at + 25 °C, + 75 °C and − 40 °C. The combined effect of vibration and temperature could certainly be relevant during in-use situations. However, a malfunction of the cooling and/or heating unit of the vehicle is required to observe such extreme temperatures.

Fig. 3a highlights how regulation UN/ECE-R100.02:2013 [62] requires significantly milder requirements compared to the other standards. Additionally, this regulation is one of the few documents that require performing the test in only one axis (vertical axis), whereas other standards require testing in two or three axes.

Vehicle level testing can also be performed as mentioned in SAE J2929:2013 [66] under conditions defined by the testing body.

3.2. Electrical tests

In this section the series of abusive tests to evaluate the electrical safety of the devices will be presented: external short circuit or short circuit protection test, internal short circuit test and overcharge/over discharge protection tests. Some other standards, which do not describe abusive tests, but still of relevance to electrical safety are also mentioned: general electrical functional safety requirements of electrically propelled road vehicles are specified in the international standard ISO 6469 series. Part 1 of this standard particularly covers the Rechargeable Energy Storage System (RESS) safety specification [103], while part 3 deals with general protection against electric shock [104] and part 4 deals with post-crash safety requirements, aimed at the protection of persons inside and outside the vehicle [105]. ISO 17409:2015 [106], deals with the safety of the electric vehicle during conductive charging. This document, which was initially part of the IEC 61851:2010 [107] series, focuses on electrical risks. Another document for wireless charging, ISO 19363 [108], is in an earlier stage of development (preparatory stage).

3.2.1. External short circuit test

The purpose of this test is to evaluate the safety performance of a DUT when applying an external short circuit. The test can evaluate the activation of the overcurrent protection device or the ability of cells to withstand the current without reaching a hazardous situation (e.g. thermal runaway, explosion, fire). The main risk factors are heat generation at cell level (thermal runaway [109]) and arcing which may damage circuitry or may lead to reduced isolation resistance.

The most relevant test parameters are presented in Table 10. During the test a low resistance element (e.g. 5 mΩ [62,70,72], 20 mΩ [63,68] or 100 mΩ [67]) is connected externally across the battery terminals in less than one second and maintained for a defined period of time (e.g. 10 min). As a consequence, current flows through the system until an overcurrent protection device – if present – limits the current [72]. Typically fuses, circuit breakers (passive elements) and contactors (active elements) are used to protect against overcurrents at module or pack level. At cell level, built in current interruption devices (CID) or positive thermal coefficient (PTC) devices can be used, which disconnect the internal current collector from its terminal or limit the passage of current if the inside pressure and/or temperature reach a certain limit. All these protection devices have a time characteristic (e.g. for circuit breaker IEC 60898-1:2015 [110]) of how quickly they limit or interrupt the current. The higher the current,

Table 10
Test conditions for the short circuit test at cell (C), module (M) and pack (P) level.

Region of applicability	International				EU and further countries[#]	USA			Korea	India	China
Short circuit parameters	**SAE J2464** [61]	**SAE J2929** [66]	**ISO 12405-1 (2) (3)** [67–69]	**IEC 62660-2 (3)** [70,71]	**UN/ECE-R100.02** [62]	**UL 2580** [63]	**USABC** [72]	**Freedom CAR** [65]	**KMVSS 18-3** [73]	**AIS-048** [74]	**QC/T 743** [75]
Level (C, M, P)	C M P	P	P	C	C M P	C M P	C M P		P	C M P	C P
Cooling medium	Operational	Operational if necessary for operation	Operational if necessary for operation				Operational				
Passive short-circuit Protection device	Disabled or bypassed (C M P) or Operational (C M)	Operational	Operational		Operational if relevant to the outcome of the test		Operational			Operational	
Non-passive protective device							Disabled			Disabled	
Resistance (mΩ)	Hard short: ≤ 5 and < < DUT DC impedance Soft short: ≥ 10 and resistance comparable to DUT DC resistance	100 (20) (ISO 12405–1(2) [67,68]) or 100 (UN 38.3 [76])[d]	100 (20)([c])	≤ 5	≤ 5	≤ 20 (UL 1642 [114]) or 5 (C) ≤ 20 (M, P)	≤5[a]		50	≤ 5[b]	< 5
SOC (% rated capacity)	95–100	95–100% max. normal vehicle operation	100	100	> 50% max. operating SOC	Max. operating SOC	100		Max. operating range of a vehicle or 80% SOC	100	100

[#]Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.
[a] For systems with ≤ 5 mΩ internal resistance, a conductor of 1/10 of the minimum resistance of the cell/module shall be used.
[b] For systems with ≤ 0.9 mΩ V^{-1} system voltage ± 0.1 mΩ internal resistance, a conductor of 1/10 of the minimum resistance of the cell/module shall be used.
[c] ISO 12405-3: the test can be conducted at a lower resistance or higher temperature than specified in ISO 12405-1 (2), as appropriate for the DUT, according to agreement between the customer and the supplier.
[d] Test temperature 55 ± 2 °C.

the faster they are typically able to interrupt it. If the current is not high enough (e.g. at low SOC) or if it drops quickly [111] the current may be not interrupted, potentially creating a hazardous situations. Therefore, standards require a hard short circuit when the external resistance is minimal [62,70,72] or a soft short circuit when the external resistance is comparable with of the internal resistance of the DUT. In this case, the soft short circuit will assure that the response of the cell is evaluated, rather than that of the protection device [61].

As mentioned, standards require a fixed external resistance irrespective of the size of the DUT. However, the initial short circuit current is influenced by the size of the DUT [112,113] as well as by its type of connection (i.e. parallel, serial or a combination thereof). Consequently, applying the same external resistance to DUTs having different sizes and types of connection, may result in not necessarily comparable initial short circuit currents per cell. Therefore some standards indicate for hard short conditions, that the external resistance needs to be much smaller than the DUT DC impedance [61] or 1/10 of the minimum resistance of the cell/module for systems with less than 0.9 mΩ V^{-1} system voltage $\pm$ 0.1 mΩ internal resistance [74], as the initial short circuit current depends on the internal resistance of the DUT. For soft short conditions, when the external short circuit resistance is higher than that of the DUT, the initial short circuit current is governed primarily by the external resistance, therefore resulting in initial short circuit currents independent of the size of the RESS.

Temperature affects the internal resistance of a battery, i.e. the rate of electrochemical reactions and transport; therefore a higher initial current can be generated at elevated temperature, which creates more heat. Moreover the higher the temperature, the closer the DUT temperature is to the onset temperature of thermal runaway. At low temperature, the activation of the protecting device (e.g. fuse, circuit breaker) can be inhibited, or the time to interruption may increase. Only UN 38.3:2015 and UL 1642:2007 require a short circuit test to be performed at a temperature higher than room temperature (55 $\pm$ 5 °C) [76,114]. Standards and regulations specific to electric vehicle applications (Table 10) do not require increased temperature testing. However, it may be considered reasonable that the short circuit test needs to be performed at temperatures higher than room temperature, which are likely to be reached during driving or when the cooling system is malfunctioning. In addition, none of the standards and regulations considers low temperature as a safety problem, where dendrite formation is prone to occur.

Another parameter that influences greatly the outcome of the test is the SOC. The worst case is achieved at high SOC, as the initial short circuit current created is maximum [112] and the onset temperature of thermal runaway is lowest [115]. Consequently, most of the standards require testing at 100% of the rated capacity (Table 10), however in the case of UN/ECE-R100.02:2013 [62], the test can be performed at 50% SOC (or above) of the maximum operating SOC value.

3.2.2. Internal short circuit test

Standardisation of the internal short circuit (ISC) test is under development, and no regulation dealing with batteries for automotive applications requires this test. The occurrence of internal short circuits, one of the main concerns for battery manufacturers, potentially leads to venting, thermal runaway, along with sparking which can ignite the electrolyte vapours escaping from the cell [57,116]. The generation of these internal shorts can be triggered by manufacturing imperfections, presence of impurities in the cells, dendritic growth of lithium etc. [57] and leads to most of in-field safety incidents [117]. Multiple internal short circuits scenarios are possible (e.g. electrical contact of cathode/anode, aluminium current collector/copper current collector, aluminium current collector/anode) each with a different contact resistance [117].

As mentioned previously, mechanical nail penetration tests aim at investigating the effects of an internal short circuit, however some works suggest that nail penetration is not representative of real field situations [57,118]. For this reason, various alternative tests have been developed in order to represent a more realistic scenario; however these tests have not been widely implemented in the legislative landscape. We will summarize here three of the most relevant tests:

3.2.2.1. Separator shutdown integrity test. The purpose of this test is to evaluate the efficiency of the shutdown separator at high temperatures and the possible failure propagation within cells connected in series (in a module) as described in SAE J2464:2009 [61]. In this test the cell shall be heated to a temperature slightly above the shutdown temperature (i.e. ≥ 5 °C). For detailed explanation on how to measure the shutdown temperature, please refer to the standard. Once the temperature is stable for 10 min, a voltage above (or equal to) 20 V is applied at a maximum current of 1 C and maintained for 30 min (or until separator failure).

3.2.2.2. Forced internal short circuit or nickel particle test. The international standards IEC 62133-2:2017 [119] and IEC 62660-3:2016 [71] provide detailed instructions for the internal short circuit test for cylindrical and prismatic type cells. The test, which is performed at two temperatures, +10±2 °C and + 45±2 °C, requires the disassembly, insertion of an L-shaped nickel particle (e.g. between positive coated area and negative coated area, between positive active material and separator) and reassembly of the cell. A short circuit is subsequently induced with a pressing machine at a speed of 0.1 mm s^{-1}.

This test has obvious drawbacks due to the need to manipulate the cell. As an alternative, the particle could be introduced during the manufacturing process.

3.2.2.3. Blunt rod indentation test. Another ISC variation, also referred to as Indentation-Induced ISC (IIISC) was developed by Underwriters Laboratories and NASA [120]. It entails the application of a mechanical force to the cell/battery, using a blunt rod instead of a sharp one, in order to deform the most outer electrode layers and eventually create a short circuit. The rod speed applied is several orders of magnitude lower than that used for the penetration tests (0.01 cm s^{-1} vs. 8 cm s^{-1}).

Overall, it can be concluded that these alternative tests exhibit uncertainties and difficulties, mostly from a practical point of view. Researchers are still actively looking for ways to evaluate the ISC hazard in a more realistic and practical way, allowing successful implementation of these tests in future automotive safety tests. Alternative approach taken by some battery manufacturers consists on designing systems where cell to cell propagation is hindered or designing packs able to contain a potential thermal runway within.

3.2.3. Overcharge/overdischarge test

In order to evaluate the functionality of the overcharge/overdischarge protection system, the battery is charged or discharged beyond the limits recommended by the manufacturer, situations that could occur due to a charger failure, for example. The relevance of the test is underlined by the fact that almost all evaluated standards and regulations (with the exception of overdischarge in AIS-048:2009 [74]) require its application. A summary of test parameters is presented in Table 11.

The main safety risks during overcharge are the decomposition of the electrolyte [109,121], cathode and anode breakdown, exothermic decomposition of the SEI layer, separator degradation, and the Li plating [122], which can lead to self-heating of the battery and thermal runaway. Also fluorinated binders, such as polyvinilidene fluoride (PVDF), have been found to react exothermically with lithiated carbon

Table 11
Test conditions for the overcharge/overdischarge test at cell (C), module (M), pack (P) and vehicle (V) level.

Region of applicability	International				EU and further countries[#]	USA			Korea	India	China
Overch./disch. parameters	**SAE J2464** [61]	**SAE J2929** [66]	**ISO 12405-1 (2)(3)** [67–69] ###	**IEC 62660-2 (3)** [70,71]	**UN/ECE-R100.02** [62]	**UL 2580** [63]	**USABC** [72]	**FreedomCAR** [65]	**KMVSS18-3** [73]	**AIS-048** [74]	**QC/T 743** [75]
Overcharge											
Level (C, M, P,V)	C M P	P	P	C	C M P V	C M P	C M P	M P	P	C M P	C P
Passive overcharge Protection device	Operational	Operational	Operational		Operational if relevant to the outcome of the test	Operational	Operational				Electronic protection circuit removed'
Non-passive protective device	Disabled	Disabled	Disabled				Disabled				
Charge rate	a) 1C CC and b) at max. current supplied by regenerative braking or charging system (or 3C) (C) 1C CC (M, P)	Max. possible rate for the application	5C (HP) 2C (HE)	$5I_t$ (HEV) $1I_t$ (BEV)	≥ C/3 and < max. current within the normal operating range specified by the manufacturer	$5I_t$ (HEV) (C) $1I_t$ (BEV) (C) Max. specified charging rate (M, P)	32 A CC* and < 450 Vdc		According to manufacturer's recommendation or 32 A CC until 1.5 x rated voltage followed by constant voltage	C/10	$3I_3$ (≈ 1C) $9I_3$(≈ 3C)
End of charge	> 200% SOC or destructive factor (e.g. thermal runway)	+	> 130% SOC, > 55 °C or ++	2 V_{max} reached or 200% SOC	++ or 2 x rated capacity	2 V_{max} reached or 200% SOC (C) +++ or 110% rated capacity, or a manufacturer specified limit or DUT failure (explosion, fire) (M, P)	200% SOC or 4 h	200% SOC or 4 h or DUT fail	150% SOC or 2.5 h after full charging	10 h	5 V or 90 min 10 V
Overdischarge											
Level (C, M, P,V)	C M	P	P	C	C M P V	C M P	C M P	M P	P		C P
Passive overdischarge Protection device	Operational	Operational	Operational		Operational if relevant to the outcome of the test	Operational	Operational				Electronic protection circuit removed'
Non-passive protection device	Disabled	Disabled	Disabled				Disabled				
Discharge rate	Max. recommended current	1C (HEV/PHEV) C/3 (BEV)	1C (HP) C/3 (HE)	$1I_t$	≥ C/3 and < max. current within the normal operating range specified by the manufacturer	$1I_t$ (C) Max. specified discharge rate (M, P)	1C		1C		I_3(≈ C/3)
End of discharge	− 100% SOC (C) or 0.0 ± 0.2 V (M)	** or 0 ± 0.2 V	25% of nominal	90 min	++ or 25% of nominal voltage	##(M, P) 90 min (C)	1.5 h or until every	1.5 h or until 50% of subassemblies have	30 min		0 V (C) A cell is 0 V (P)

(continued on next page)

Table 11 (*continued*)

Region of applicability	International				EU and further countries[#]	USA			Korea	India	China
Overch./disch. parameters	**SAE J2464** [61]	**SAE J2929** [66]	**ISO 12405-1 (2)(3)** [67–69] ###	**IEC 62660-2 (3)** [70,71]	**UN/ECE-R100.02** [62]	**UL 2580** [63]	**USABC** [72]	**FreedomCAR** [65]	**KMVSS18-3** [73]	**AIS-048** [74]	**QC/T 743** [75]
			voltage, 30 min after passing the normal discharge limits or ++				cell is reversed for 15 min	achieved voltage reversal for 15 min			

CC: constant current. I_t : current in amperes which is expressed as It (A) = Cn (Ah)/1 (h) where Cn is the rated capacity of the cell ; n is the time base (hours) for which the rated capacity is declared. V_{max} maximum voltage specified by the manufacturer. + Until the charge device voltage is reached or the connection interface disconnects battery from charge device. ++ Until the DUT interrupts the charging (discharging) by an automatic disconnect of the main contactors. +++ Termination by protective circuitry whether it is due to voltage or temperature controls. #Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia. ## Until the passive protection device(s) are activated, the minimum cell voltage/maximum temperature protection is activated, or the DUT has been discharged for an additional 30 min after it has reached its specified normal discharge limits, whichever comes first. ### Higher temperature can be used according to agreement between the customer and the supplier. *When performing this test at less than the pack level, the voltage (series pack configuration) or the voltage/current (series/parallel pack configuration) shall be scaled down appropriately. ** Until the connection interface disconnects battery from discharge load.

Table 12
Test conditions for the thermal stability test at cell (C), module (M) and pack (P) level.

Region of applicability	International				EU and further countries[#]	USA			Korea	India	China
Thermal stability parameters	**SAE J2464** [61]	**SAE J2929** [66]	**ISO 12405-1 (2)(3)** [67–69]	**IEC 62660-2 (3)** [70,71]	**UN/ECE-R100.02** [62]	**UL 2580** [63]	**USABC** [72]	**FreedomCAR** [65]	**KMVSS18-3** [73]	**AIS-048** [74]	**QC/T 743** [75]
Level (C, M, P)	C			C		C	C M P		P		C P
Heating rate ($C\ min^{-1}$)	≥ 5			5		5		5–10			
Heating steps	5 °C						5 °C (C) 10 or 20 °C (M, P)	5 °C (C) 10 °C (M, P)			
Termination	300 °C above maximum operating temperature or catastrophic event			130 ± 2 °C		130 ± 2 °C	Additional self-heating is detected or 200 °C above maximum operating temperature or catastrophic event		80 ± 2 °C		85 ± 2 °C
Holding time (min)	30 or until self-heating[a]			30		30	30 (C) 120 (M, P) or until self-heating		240		120
Repetition in case of self-heating[a]	2 °C heating steps - hold for > 1 h						2 °C heating steps - hold for > 1 h (C)	2 °C heating steps - hold for > 1 h			
SOC (% rated capacity)	95–100 or lower SOC at which thermal stability is degraded			80 (HEV) 100 (BEV)		80 (HEV) 100 (BEV)	100		Max. operating range of a vehicle or 80% SOC		100

#Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.

[a] Self-heating is defined when temperature increases at a rate higher than 1.0 °C min^{-1}.

Table 13
Test conditions for the thermal shock test at cell (C), module (M) and pack (P) level.

Region of applicability	**International**					**EU and further countries**[#]	**USA**			**Korea**	**India**	**China**
Thermal Shock parameters	**SAE J2464** [61]	**SAE J2929** [66]	**ISO 12405-1 (2)(3)**[a] [67–69]	**IEC 62660-2 (3)**[a] [70,71]		**UN/ECE-R100.02** [62]	**UL 2580** [63]	**USABC** [72]	**Freedom CAR** [65]	**KMVSS 18-3** [73]	**AIS-048** [74]	**QC/T 743** [75]
Level (C,M, P)	C M P	C M P	P	C		C M P	C M P	C M P				
Protection device	Active thermal controls (primary and secondary) disabled	Not defined in UN 38.3 alternative	Thermal controls disabled	Without electrical operation	With electrical operation	Protection devices shall be operational	Active thermal controls (primary and secondary) disabled	Thermal controls (primary and secondary) disabled				
T_{max} (°C)	+ 70 ± 2 or ± 5% of reading	+ 70 ± 2 or ± 5% of reading or + 72 ± 2	+ 8 5 ± 1[b]	+ 85 ± 2	+ 65 ± 2	+ 60 ± 2	+ 85 ± 2	+ 80				
T_{min} (°C)	− 40 ± 2 or ± 5% of reading		− 40 ± 1	− 40 ± 2	− 20 ± 2	− 40 ± 2	− 40 ± 2	− 40				
Hold time (h)	≥ 1 (C) ≥6 (M)[c] (P)	≥ 1 (C) ≥ 6 (M)[c] (P) or ≥ 12 (C > 0.5 kg M, P > 12 kg)	≥ 1 6 (3)	1.5 (T_{min})	1.83 (T_{max})	6	1.5 (T_{max}) (C) 1.83 (T_{min}) (C) ≥ 6 (M)[c] (P)	Appropriately adjusted (C) ≥ 6 (M) appropriately adjusted (P)	≥ 1 (C) ≥ 6 (M)[c] (P)			
Repetitions	5	5 or 10	5	30		5	30	5				
SOC (% rated capacity)	95–100	95–100% max. normal vehicle operation	50 (HP) 80 (HE)	80 (HEV) 100 (BEV)	60 (HEV) 80 (BEV)	≥ 50% max. operating SOC	80/60 (HEV) 100/80 (BEV) (C) Max. operating SOC (M, P)	50				

[#]Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.

[a] Or T_{min} T_{max} as specified by manufacturer.

[b] Part 3 of the standard allows: + 60 ± 2 °C with a hold time of 6 h.

[c] As required to reach uniform temperature (± 5 °C).

Table 14
Test conditions for the overheat test at cell (C), module (M), pack (P) and vehicle (V) level.

Region of applicability	International				EU and further countries#	USA			Korea	India	China
Over heat parameters	**SAE J2464** [61]	**SAE J2929** [66]	**ISO 12405-1 (2)(3)** [67–69]	**IEC 62660-2 (3)** [70,71]	**UN/ECE-R100.02** [62]	**UL 2580** [63]	**USABC** [72]	**FreedomCAR** [65]	**KMVSS 18-3** [73]	**AIS-048** [74]	**QC/T 743** [75]
Level (C, M, P, V)	M P	P			C M P V			M P			
Protection device	Active thermal controls (primary and secondary) disabled	Cooling system deactivated			Cooling system deactivated		Active thermal controls (primary and secondary) disabled				
Charge rate	As defined by the manufacturer	Max. normal rate			Steady current that will increase the temperature of cells as rapidly as possible within the range of normal operation defined by the manufacturer		1C	Manufacturer's recommended charge algorithm			
Discharge rate	Rate comparable to the intended application						1C	Rate comparable to a 3 kW constant power rate for entire DUT			
Number of cycles	20							20			
SOC (% rated capacity)	95–100	Max. normal operating SOC						100			

#Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.

if sufficient temperature is reached (e.g. 200 °C [60]). Factors affecting the outcome of the test are amongst others, the charging rate and the finally reached SOC.

For the overcharge test, a controlled current is applied to the battery (e.g. 1/3 I_t[2] -rate) up to a set charge limit (e.g. 200% SOC [61,62,70,72], 110% SOC [63], 130% [67]) or until the tested-device (automatically) interrupts or limits the charging. Although most of the standards provide a general description for all types of energy storage devices, others describe specific tests for EVs, HEVs and PHEV applications (e.g. charging rate at 5 I_t [123] for HEV and 1 I_t for BEV [70,71]). Some other standards recommend much lower C-rate (e.g. C/10 in AIS-048:2009 [74], C/3 rate in UN/ECE-R100.02:2013 [62]). Tobishima et al. showed that cells overcharged at low rates did not show any venting whereas those cells overcharged at a 2C rate did [124]. Golubkov et al. showed that NCA cells with SOC ≤ 100% had a thermal runaway onset temperature in the range 136–160 °C, whereas overcharged cells (SOC > 100%) showed much lower onset temperatures (ranging 65–80 °C). Although serious events occur at cell level with significant overcharge (e.g. 2 times the rated capacity), repeated charge/discharge cycling at moderate overcharge (110% SOC) can also lead to internal short and failure of the cell in only 10 cycles [125].

To address another scenario of great importance, an overdischarge (or forced discharge) test is generally required. Safety risks during overdischarge are polarity reversal leading to oxidation of the anode current collector (Copper) and to plating on the cathode side. Even minor over-discharge may cause dendrite formation and finally short circuit [126]. During the overdischarge test, a fully charged battery is discharged (e.g. 1C rate for 1.5 h [65], C/3 rate) until the tested-device interrupts or limits the discharging [62]. The great variability in test parameters found in the various evaluated documents (Table 11) can lead to the conclusion that the outcome of the tests might be dependent on the standard or regulation followed. For this reason harmonisation of testing parameters is required to allow comparable testing.

3.3. Environmental tests

Environmental testing aims at evaluating the safety performance of a system under conditions of temperature change, such as an accident scenario involving fire, or extreme weather exposure in certain geographic areas. In this section, the most common environmental tests, thermal stability, thermal shock, overheat and extreme cold temperature and fire tests are described.

3.3.1. Thermal stability test

This test evaluates the stability of a battery at an elevated temperature to identify the temperature where thermal runway begins. For this test, the temperature of the cell is increased sequentially in 5 °C steps with a holding time of 30 min at each incremental step, until the temperature reaches 200 °C [65,72] above the maximum operating temperature of the battery (or until a catastrophic event occurs such as venting or major damage to the DUT). For modules and packs, the increments of temperature are set to 10 °C with a longer holding time of 120 min [65,72]. Standard SAE J2464:2009 [61] has a higher threshold temperature of 300 °C above the maximum operating temperature. These tests require a second execution in order to refine the exact start temperature of the thermal event. During the second execution, the temperature is increased in 2 °C increments and held for a minimum of one hour at each incremental step [61,65,72].

Some other standards evaluate the performance of the system at elevated temperature, not aiming at reaching thermal runaway, but at the

[2] The current It represents the discharge current in amperes during one hour discharge and C is the measured capacity of a battery pack (or a cell): It (A) = Cn (Ah)/1 (h); n is the time base (hours) for which the rated capacity is declared.

Table 15
Test conditions for the fire test at cell (C), module (M), pack (P) and vehicle (V) level.

Region of applicability	International					EU and further countries[#]	USA			Korea	India	China
Fire parameters	**SAE J2464** [61]	**SAE J2929** [66]	**ISO 12405-1 (2)** [67,68]	**ISO 12405 (3)** [69]	**IEC 62660-2 (3)** [70,71]	**UN/ECE-R100.02** [62]	**UL 2580** [63]	**USABC** [72]	**Freedom CAR** [65]	**KMVSS 18-3** [73]	**AIS-048** [74]	**QC/T 743** [75]
Level (C,M, P, V)	M P	P		P V[a]		C M P V	C M P	C M P		P		
Heat source	Radiant heat	Flame		Flame		Flame	Flame	Radiant heat		Flame		
Set-up	Cylindrical metallic fixture	Wire mesh screen (Fig. 4a)		Grating table (Fig. 4b)		Grating table (Fig. 4b)	Wire mesh screen or floor perimeter (C)[b] (Fig. 4a) Floor perimeter (M, P)	Cylindrical metallic fixture	Cylindrical fixture	Not specified		
T_{max} (°C)	890 °C	To be defined by responsible testing organisation		Not specified		Not specified	590 °C	890 °C		890–900 °C		
Holding time at T_{max}	10 min			70 s		70 s	20 min	10 min		2 min		
SOC (% rated capacity)	100			> 50% normal operating range (HP) Max. SOC at normal operation (HE)		> 50% max. operating SOC	Fully charged (C) Max. operating SOC (M, P)	≥ 80	100	Max. operating range of a vehicle or 80% SOC		

[#]Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.

[a] The vehicle body may be included.

[b] The overall dimensions of the projectile test aluminium test screen may be increased to accommodate cells with dimensions larger than 127 mm (5 in.), but shall not exceed a distance of 305 mm (12 in.) from the cell in any direction.

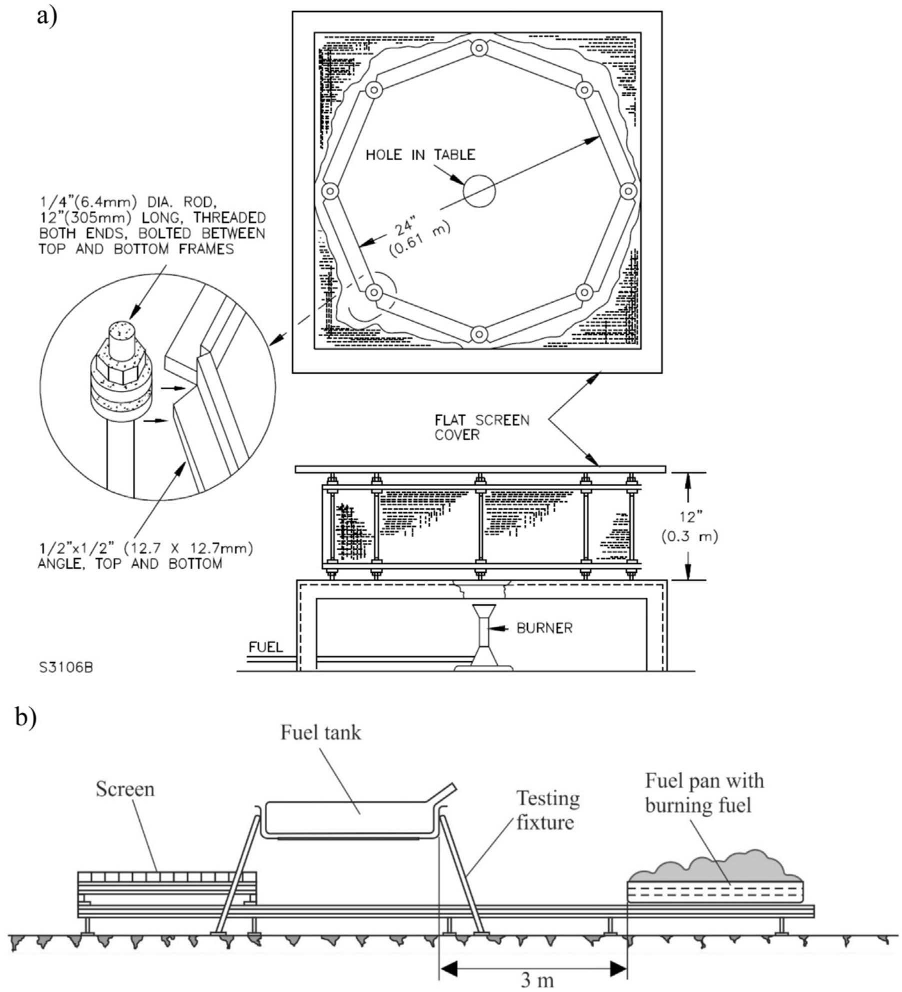

Fig. 4. Examples of fuel fire test set ups: a) wire mesh screen (copied from UL 1642 [112]) and b) grating table (copied from UN/ECE-R34 [127]). Copyright © Underwriters Laboratories Inc. UL 1642, 4th edition, 2007.

assessment of the thermal stability of the DUT at this temperature. Examples include ISO 62660-2:2011 (*High temperature endurance test*) [70], QC/T 743:2006 (*heat test*) [75] and KMVSS18-3:2009 (*Heat exposure test*) [73] as they require placing the battery in a chamber and increasing the temperature to only 130 °C, 85 °C and 80 °C, respectively.

Although it seems that both variants of the test provide useful insight into the safety of the energy storage system, they are not widely required as can be seen in Table 12.

3.3.2. Thermal shock test

This test is designed to evaluate changes in the integrity of the DUT arising from expansion and contraction of cell components upon exposure to extreme and sudden changes in temperature (e.g. the vehicle is entering or exiting a heated garage, during transport [63]) and potential consequences of such changes. During a thermal shock the DUT is exposed to two temperature limits and held at each temperature limit for a specified period of time. The thermal shock tests described in standards have different maximum temperature limits (see Table 13). ISO 12405-1:2011 [67], ISO 12405-2:2012 [68], IEC 62660-2:2011 [70] and UL 2580:2013 [63] have set the highest upper limit at +85 °C, while the lowest upper limit is set at +60 °C in UN/ECE-R100.02:2013 [62]. The lower temperature limit is − 40 °C in all the cases.

Noteworthy is that amongst all the documents evaluated, only UN/ECE-R100.02:2013 [62] permits operation of the protection devices during this test. In the other standards the protection device is disabled, which imposes harder testing conditions.

3.3.3. Overheat test

The overheat test, also referred to as *rapid charge/discharge, cycling without thermal management, single point thermal control system failure, over-temperature protection* test, aims at evaluating the effect of temperature control failure or failure of other protection features against internal overheating during operation. Test parameters required in this test are displayed in Table 14.

For this test, a fully charged DUT, whose active thermal control system (e.g. cooling system) is disabled, is cycled (e.g. 20 cycles with no resting period between charge and discharge [61,66]). As a consequence, the temperature of the DUT will increase. According to some standards, the test must be performed in a closed volume in order to evaluate the flammability of any materials being released from the battery during the test [61,65,66,72]. In this case, a spark source has to be present to ignite any potentially flammable gases or vapours from the DUT or, alternatively, a gas concentration measuring device can be utilized as suggested by SAE J2929:2013 [66].

In the case of UN/ECE-R100.02:2013 [62], the test is stopped when either: (a) the DUT interrupts the charging/discharging to prevent temperature increase, (b) the temperature of the DUT is stable (i.e. variation $<$ 4 °C in 2 h) or (c) there is evidence of DUT damage (e.g. electrolyte leakage, rupture, fire or explosion).

3.3.4. Extreme cold temperature test

The rationale behind this test is the effect of possible exposure of the DUT to low temperatures (e.g. vehicle parked in a cold environment). At low temperatures, the electrolyte has poor ionic conductivity and the anode experiences high over-potentials [127] with can lead to dendrite formation. Metallic plating can be a safety concern because growing dendrites could short circuit the cell. Despite these issues, only one standard deals with this topic. USABC:1999 [72] describes a matrix for charging at the normal primary charge rate for the specific system and discharging at 1C down to various DOD's (depths of discharge): 20, 50, 60, 80, 100% at the following temperatures: − 40, − 20, 0 and 25 °C [72]. The liquid coolant is present, but not circulating during the test. The test shall be stopped if abnormal conditions (e.g. voltage, temperature) or physical damage to the DUT becomes evident.

3.3.5. Fire test

The objective of the fire test is to expose a battery or a vehicle to a fire and assess the risk of explosion. The source of the fire can be spilled fuel either from the vehicle itself or a nearby vehicle. This test it is often termed *Fuel fire test* but can be also called: *Radiant heat, Projectile fire, External fire simulation, Exposure to simulated vehicle fire, High-temperature hazard or Fire resistance* test. Table 15 displays test parameters. Three types of the test are described:

i) *Radiant-heat test:* the battery (e.g. ≥ 80% SOC [72], 100% SOC [61,65]) is placed inside a cylindrical metallic fixture, which is externally heated by means of radiant heat (e.g. quartz lamps, tube furnace and conveyor mechanism). A temperature of 890 °C shall be reached in less than 90 s and held for 10 min. Hazardous substance monitoring (e.g. EPA Methods TO-15 [128] and TO-17 [129]) is performed by sampling of combustion products to determine the possible presence of hazardous gas species released during the test [61,65].
ii) *Projectile test*: in this case the DUT, exposed to a uniform fire, is surrounded by a steel wire mesh screen in a way that no part of an exploding cell or battery can penetrate through the mesh (e.g. 0.25 mm diameter wire and grid density of 6–7 wires cm^{-1}) (Fig. 4a) [63,66].

UL 2580:2013 requires testing at least at 590 °C for a duration of 20 min [63]. In this case, the use of a mesh screen is not mandatory and as alternative the DUT can be placed within a circular inner perimeter area (e.g. < 1 m marked on the floor). No explosion of the DUT that results in projectiles falling outside of this perimeter is allowed. A second outer perimeter (around 1.5 m from inner perimeter) made of a non-combustible material surrounds the inner perimeter.

i) *Grating table configuration test*: this test as described in UN/ECE-R100.02:2013 [62] is an adaptation from UN/ECE-R34:2012 - Annex 5 [130], where a flame is created by burning fuel in a pan. The DUT shall be placed on a grating table positioned above the pan (Fig. 4b). The different steps of the test require first the preheating of the DUT during 60 s by placing the burning fuel pan at a distance of 3 m. Then, the DUT is directly exposed to the flame for another 70 s. Immediately after, a screen of refractory material is placed in between the pan and the DUT in order to reduce the flame for further 60 s as depicted in Fig. 4b. This test is passed if there is no evidence of explosion during the test.

Only two standards, SAE J2464:2009 [61] and UL 2580:2013 [63] highlight the importance of quantifying toxic and determining flammable emissions providing suitable testing procedures (see Section 3.4 for further details). Although it has been proven by various authors that significantly higher amounts of, for example HF, are generated in EV fires compared to ICE vehicle fires (e.g. 1500 g compared to 600–800 g, respectively [131–133]), the implementation of analysis of emissions is not widely adopted. Moreover, with such a variation of conditions and requirements for the fire test, it seems clear that the comparability of test results is not ensured.

3.4. Chemical hazards evaluation tests

Lithium ion batteries contain, as mentioned in the introduction, significant amounts of potentially hazardous materials (e.g. highly flammable electrolytes, corrosive and toxic components [16,134,135]). If exposed to certain conditions, it is expected that the integrity of the battery is compromised which may lead to electrolyte leakage, venting, rupture or even fire and explosion. Amounts of gas released from various 18650 cells during a thermal runaway event have been measured to be around 1.2 l $(A\,h)^{-1}$ [87,136] for various cathode materials. Golubkov et al. found higher amounts of vented gas on LCO/NMC batteries (e.g. 2.3 l $(A\,h)^{-1}$ as calculated from 0.27 mol of gas released) [10]. The gases being released are composed of a mixture of species: carbon monoxide, carbon dioxide, methane, hydrogen, oxygen, ethane, ethylene, hydrofluoric acid as measured in various studies [10,35,131,137,138]. The exposure of persons in the vicinity of such compromised batteries can lead to serious injuries (e.g. eye irritation, chemical burns, poisoning, abrasion, skin injuries). Thus, it is of importance to identify and quantify substances being released from the battery during tests representing misuse and abuse events and to ensure that the amounts released are not hazardous to vehicle occupants and first aid responders. Within this context, the development of warning sensors for passengers, first aid responders and rescue workers has been advised [82]. For example, fire brigades include in their guidelines advice related to the chemical risks of batteries for EVs and HEVs (i.e. gas and liquid releases) such as: use of full PPE (personal protective equipment), avoid standing close to hot battery remnants and avoid inhaling the fumes under any circumstances [139–141].

3.4.1. Emissions related tests

Some standards require hazardous substances measurements (e.g. gas, smoke, flames, and particulates) and for this analytical techniques or gas sensors are recommended. Moreover, many standards require that the amounts measured need to be below certain concentrations [61,63,65,66,72], such as those defined by the Emergency Response Planning Guidelines ERPG-2 [142], from the American Industrial Hygiene Association [143] or other industry practice documents or standards such as from the Occupational Safety and Health Administration (OSHA) [144], Acute Exposure Guidelines Levels from the Environmental Protection Agency (EPA) [145], Short-Term Exposure Limits (STEL) [146].

SAE J2464:2009 [61] points out that the concentration of the released hazardous substances shall be scaled to the full pack for quantitative comparison and scaled to a volume appropriate to human exposure in the vehicle (e.g. below ERPG-2 level: maximum airborne concentration levels below which most individuals could be exposed for up to one hour without experiencing or developing serious or irreversible health effects or symptoms which could impair an individual's ability to take protective action).

When manufacturers indicate the possibility that toxic gases can be released during abusive conditions, gas monitoring is needed during the tests by utilizing one of the following techniques (or equivalent) as described in UL 2580:2013 [63] and SAE J2464:2009 [61]:

- ASTM (the American Society for Testing and Materials) D4490: standard practice for measuring concentrations of toxic gases of vapours using detector tubes [147].
- ASTM D4599: standard practice for measuring concentrations of toxic gases of vapours using length-of-stain dosimeters [148].
- OSHA: Evaluation guidelines for air sampling methods utilizing spectroscopic analysis [149].
- NIOSH (The National Institute for Occupational Safety and Health): Manual for analytical methods [150].
- EPA Methods TO-15 [128] for the determination of VOC's (volatile organic compounds) in air analysed by Gas Chromatography and Mass spectrometry.

- EPA Methods TO-17 [129] for the determination of VOC's in air using active sampling onto sorbent tubes.

More sophisticated devices for gas detection of evaporated compounds can be Fourier Transformed Infrared Spectroscopy (FTIR) and mobile detection systems (e.g. detection of O_2, CO, H_2, C_2H_4O, HF and of toxic VOC's as used by German fire brigades [82]).

Standard SAE J6469-1:2009 [103] requires that potentially dangerous concentration of hazardous gases or other hazardous substances shall not be allowed anywhere in the driver, passenger and load compartments. The maximum allowable quantity accumulated during testing of hazardous gases and other substances (for normal operating and environmental conditions) shall refer to the latest version of applicable National/International standards or regulations.

UN/ECE-R100.02:2013 [62] regulates emissions from open-type traction batteries, which may produce hydrogen gas during normal operation. The quantification of hydrogen during normal charging follows the protocol indicated in the regulation and must remain below certain limits (i.e. below 25 x h (g)). Other gases are not considered. Systems with a closed chemical process, such as LIBs, are considered 'emission free' (i.e. do not emit gases under normal operation). In the case of abusive conditions, this regulation does not enforce any requirements or limitations for emissions of hazardous gases (e.g. venting) from any type of rechargeable energy storage systems. An improvement of the regulation in this regard could be of high importance to ensure the safety of users and first aid responders.

3.4.2. Flammability tests

In abusive conditions, it is possible that LIBs emit flammable gases (e.g. methane, ethane, hydrogen, carbon monoxide). SAE J2929:2013 [66], for example, highlights this hazard and recommends that consideration should be given to preventing the build-up of flammable gases that could get in contact with vehicle ignition sources (e.g. sparks from a short circuit, fire in the vicinity). Determination of the flammability of any substance (e.g. liquid, solid materials) emitted from the battery is mandatory in many standards [61,63,65,66,72]. One method is to incorporate one or several spark ignition source(s) in the testing area, located close to the DUT. Alternatively, gas monitors can also be used, as mentioned in UL 2580:2013 [63]. On the contrary, some other standards do not give indications on how to assess this property, e.g. UN/ECE-R100.02:2013 [62].

Overall it can be concluded that the evaluation of chemical hazards is tackled very differently in the various standards and regulations. In some cases, such as in SAE J2464:2009 [61], SAE J2929:2013 [66] and UL 2580:2013 [63], detailed information on quantifying and determining toxicity and flammability of LIB emissions is provided, while in other cases this issue is only slightly mentioned, such as in UN/ECE-R100.02:2013 [62]. In some instances chemical hazards are not even considered, such as in ISO 12405-1(2,3):2001(2012,2014) [67–69], IEC 62660-2(3):2001(2013) [70,71], KMVSS 18-3:2009 [73], AIS-048:2009 [74] and QC/T 743:2006 [75]. Taking into consideration the importance of the issue, it would be advisable that future standardisation/regulation developments consider a harmonized testing guidance or protocol to ensure that chemical hazards of automotive batteries are appropriately assessed.

4. Current evolutions and future perspectives

International standards on lithium traction battery safety are being developed by ISO and IEC, focusing respectively on system and cell level. Documents already published by ISO include ISO 12405-1:2011 and 12405-2:2012 [67,68], defining test specifications for high-power (for hybrids) and high-energy batteries (for battery electric vehicles), respectively. Both these documents were complemented with the recently published ISO 12405-3:2014 [69], which sets pass/fail requirements to the precedent documents. Chinese counterparts were published in 2015 under GB/T 31467.1, GB/T 31467.2 and GB/T 31467.3. Within IEC, IEC62660-2 [70] was published in 2011, describing safety tests for propulsion cells. IEC 62660-3:2016 [71], defining cell safety specifications was published in 2016. Also a new standard, IEC 62485-6 [151], on safety requirements for lithium-ion batteries and battery installations is proposed.

On vehicle safety, ISO 6469-4 [105] on post-crash safety has been published in 2015.

Once published, standards go into a maintenance cycle with periodic revision at least every five years. Topics for revision may include consideration of upcoming battery technologies such as lithium sulfur, lithium air as well as lithium ion capacitors for which specific test procedures may be required. Furthermore, the use of batteries in a “second life” application will require specific test regimes to determine their state of health and their cycling in stationary applications, taking into account the specific safety requirements of the operating environment.

A Global Technical Regulation on Electric Vehicle Safety (GTR-EVS) has been submitted for a vote to the UNECE World Forum for Harmonization of Vehicle Regulations (WP.29). A decision on the adoption of this regulation is expected in November 2017.

5. Conclusions

This work presents a comprehensive review of the various standards and regulations dealing with the safety performance of lithium ion batteries to be used in electrified transport. Test parameters and conditions adopted in the test methods which are described in these standards and regulations are compared. From the analysis performed the following conclusions are drawn:

- Most of the existing standards and regulations impose test requirements derived from regulatory documents originally intended for conventional vehicles. It is clear that more analysis and data evaluation specific to EVs and HEVs is highly desirable to cover the specificities of electrified technologies. For example, recent research has indicated that battery pack installations may be exposed to vibration loads outside the range evaluated by existing standards [100].
- Another concern is whether the tests performed at component level are comparable to those carried out at vehicle level. For example, the force experienced by a DUT in a crush test (component level) or crash test (vehicle level) is expected to depend on the presence and - if present, on the properties of – mechanical protection (such as the chassis or battery enclosure).
- Comparability of component testing at cell, module and pack level should also be examined. For example, it has been proven that the initial current created in the short circuit test is influenced by the size of the DUT [112,113] as well as by its type of connection (i.e. parallel or serial). Similar influence on test outcome may be expected when applying a single crush force and crushing plate to DUTs of different sizes.
- Dispersion in test conditions (e.g. SOC, temperature) is rather wide for most tests (e.g. overcharge, thermal shock, short circuit). This has an important impact in the comparability of data obtained utilizing various standards, while in some cases differences in parameters might be due to different considered scenarios. Alignment of parameters is advisable in order to perform fair and equivalent tests. As the worst case typically corresponds to maximum SOC, it is logical that abuse testing is performed in such condition. For example, in the short circuit test, the higher the SOC value of the DUT, the higher the short circuit current generated [112] and the lower the onset temperature of thermal runaway [115]. Most standards already require 100% SOC, however regulation UN/ECE-R100.02:2013 [62] allows testing at ≥ 50% SOC.

- Real world accidents are dynamic events i.e. the battery moves towards the impact zone. However, testing at component level is carried out using static assemblies where the impactor moves towards the battery. Investigations have shown discrepancies in mechanical loads between current standards and regulations and dynamic crash tests [94,96], and for this, appropriate modifications within the regulatory framework are advisable.
- Systems intended to be removed from the vehicle for charging, swapping or replacement may be accidentally dropped during handling. Although this scenario seems plausible, the drop test is not included in various automotive battery regulations and standards, such as UN/ECE-R100.02:2013 [62], ISO 12405-1(2,3):2011(2012,2014) [67–69] and ISO 62660-2:2011 [70].
- The occurrence of internal short circuits is one of the main concerns for battery manufacturers; however these tests have not been widely implemented in the legislative landscape. It is recognized, though, that the practicalities of this test are complex and implementation of such testing would require significant research for test method development.
- Only SAE J2464:2009 [61], SAE J2929:2013 [66] and UL 2580:2013 [63] highlight the importance of determining toxic and flammable emissions and provide suitable testing procedures. The implementation of specific analysis is not widely adopted by other bodies. Taking into consideration the importance of this issue, it is advisable that future standardisation/regulation developments consider a harmonized testing guidance and protocols to ensure that chemical hazards of automotive batteries are appropriately assessed in order to ensure the safety of vehicle occupants and surrounding persons.
- In relation to safety testing, the evaluation of realistic scenarios is greatly recommended in order to ensure a safe future for the use of lithium ion battery technologies. To ensure this, the addition of some tests, such as roll over, drop, immersion, low temperature hazards, toxicity, flammability, etc. into future standards and regulations should be considered.
- Finally, clear and unambiguous testing guidelines should be provided as part of the test method and rationale description. Examples include descriptions of the method for setting the SOC, the location of temperature sensors, the exact position of the DUT in the various tests, in addition to the minimum tolerance required for the testing equipment. Such guidelines facilitate the correct and harmonized interpretation of the standard or regulation by the testing bodies and comparability of results would be improved.

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References

[1] Electric Vehicle Market Forecasts . Global forecasts for light duty hybrid, plug-in hybrid, and battery electric vehicle sales and vehicles in use: 2014–2023. Nav Res 2014.

[2] Proff H, Kilian D. Competitiveness of the EU automotive industry in electric vehicles. Duisburg: University of Duisburg-Essen; 2012.

[3] Lutsey N. Transition to a global zero-emission vehicle fleet: a collaborative agenda for goverments, international council on clean transportation transition to a global zero-emission vehicle fleet: a collaborative agenda for goverments. Int Counc Clean Transp 2015.

[4] Lithium ion rechargeable batteries technical handbook. Sony Corporation. ⟨https://www.4project.co.il/documents/doc_286_2661.pdf⟩.

[5] Lowe M, Tokuoka S, Trigg T, Gereffi G. Lithium-ion batteries for electric vehicles: the US value chain. Centre on Globalization, Governance & Competitiveness Duke University; 2010.

[6] Cluzel C, Douglas C. Cost and performance of EV batteries. final report. Elem Energy Ltd Comm Clim Change 2012.

[7] Lache R, Galves D, Nolan P, et al. Autos & auto parts electric cars: plugged in 2. A mega-theme gains momentum. FITT Res 2009.

[8] American and European standards organisations agree to strengthen transatlantic cooperation on standards for electric vehicles. The European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC); 2012. Available Online: ⟨http://www.cencenelec.eu/news/press_releases/pages/PR-2012-18.aspx⟩.

[9] Opitz A, Badami P, Shen L, Vignarooban K, Kannan AM. Can Li-ion batteries be the panacea for automotive applications?. Renew Sustain Energy Rev 2017;68(Part1):685–92.

[10] Golubkov AW, Fuchs D, Wagner J, Wiltsche H, Stangl C, Fauler G, et al. Thermal-runaway experiments on consumer Li-ion batteries with metal-oxide and olivin-type cathodes. RSC Adv 2014;4:3633–42.

[11] Jacoby M. Burning batteries, chemical & engineering news. C&EN Chem Eng News 2007;85:26–8.

[12] Lamb J, Orendorff CJ, Steele LAM, Spangler SW. Failure propagation in multi-cell lithium ion batteries. J Power Sources 2015;283:517–23.

[13] von Sacken U, Nodwell E, Sundler A, Dahn JR. Comparative thermal stability of carbon intercalation anodes and lithium metal anodes for rechargeable lithium batteries. Solid State Ion 1994;69:284–90.

[14] Chen Y, Evans JW. Thermal analysis of lithium-ion batteries. J Electrochem Soc 1996;143:2708–12.

[15] Bandhauer TM, Garimella S, Fuller TF. Temperature-dependent electrochemical heat generation in a commercial lithium-ion battery. J Power Sources 2014;247:618–28.

[16] Levy SC, Bro P. Battery hazards and accident prevention. New York and London: Plenum Press; 1994.

[17] Mikolajczak MK C, White K, Long RT. Lithium-ion batteries hazard and use assessment. Menlo Park, CA: Exponent Failure Analysis Associates, Inc, Springer; 2011 .

[18] Boeing 787 battery fire. National Transportation Safety Board (NTSB) Accident Investigations; 2013. ⟨http://www.ntsb.gov/investigations/pages/boeing_787.aspx⟩.

[19] Hazardous materials accident reports. National Transportation Safety Board. ⟨http://www.ntsb.gov/investigations/AccidentReports/Pages/hazardous.aspx⟩.

[20] Lithium battery fire risk linked to Dubai plane crash. The National; 2010. ⟨http://www.thenational.ae/news/uae-news/lithium-battery-fire-risk-linked-to-dubai-plane-crash⟩.

[21] Air accident investigation report: uncontained cargo fire leading to loss of control inflight and uncontrolled descent into terrain. General Civil Aviation Authority of the United Arab Emirates; 2010. ⟨https://www.gcaa.gov.ae/en/ePublication/admin/iradmin/Lists/Incidents%20Investigation%20Reports/Attachments/40/2010-2010%20-%20Final%20Report%20-%20Boeing%20747-44AF%20-%20N571UP%20-%20Report%2013%202010.pdf⟩.

[22] Smith B. Chevrolet volt battery incident overview report, 2012th ed.. Washington, DC: National Highway Traffic Safety Administration (NHTSA); 2012.⟨http://www.nhtsa.gov/staticfiles/nvs/pdf/Final_Reports.pdf⟩.

[23] On-site electric vehicle fire investigation. US Department of Transportation – National Highway Traffic Safety Administration; 2013.

[24] Apple says product shortage will hurt quarterly earnings: computers: company unable to keep up with consumer demand. It also is recalling new PC because of fire concern. Times, Los Angeles; 1995. ⟨http://articles.latimes.com/1995-09-15/business/fi-46242_1_many-apple-computers⟩.

[25] CPSC and EV Global Motors Co . Announce recall of lithium batteries in electric bikes. United States: Consumer Product Safety Commission; 2002. ⟨https://www.cpsc.gov/Recalls/2002/CPSC-and-EV-Global-Motors-Co-Announce-Recall-of-Lithium-Batteries-in-Electric-Bikes-/⟩

[26] Ogumi Z, Wang H. Chapter 3: carbon anode materials. In: Yoshio Masaki, Brodd Ralph J, Kozawa A, editors. Lithium-ion batteries science and technologies. New York, NY: Springer; 2009. p. 51.

[27] Zhang SS. A review on electrolyte additives for lithium-ion batteries. J Power Sources 2006;162:1379–94.

[28] Illig J, Chrobak T, Ender M, Schmidt JP, Klotz D, Ivers-Tiffée E. Studies on $LiFePO_4$ as cathode material in Li-ion batteries. In: Proceedings of the batteries and energy technology joint general session – 217th ECS meeting, 30 ed. Vancouver, BC; 2010, p. 3-17.

[29] Saw LH, Ye Y, Tay AAO. Electrochemical–thermal analysis of 18650 lithium iron phosphate cell. Energy Convers Manag 2013;75:162–74.

[30] Nitta N, Wu F, Lee JT, Yushin G. Li-ion battery materials: present and future. Mater Today 2015;18:252–64.

[31] Balakrishnan PG, Ramesh R, Prem Kumar T. Safety mechanisms in lithium-ion batteries. J Power Sources 2006;155:401–14.

[32] Zhu G-N, Du Y-J, Wang Y-G, Yu A-S, Xia Y-Y. Electrochemical profile of lithium titanate/hard carbon composite as anode material for Li-ion batteries. J Electroanal Chem 2013;688:86–92.

[33] Nowack LV, Waser O, Yarema O, Wood V. Rapid, microwave-assisted synthesis of battery-grade lithium titanate (LTO). RSC Adv 2013;3:15618–21.

[34] Reddy T. Linden's handbook of batteries, 4th edition. New York, NY: McGraw-Hill, Inc.; 2011.

[35] Campion CL, Li W, Lucht BL. Thermal decomposition of LiPF 6-based electrolytes for lithium-ion batteries. J Electrochem Soc 2005;152:A2327–A2334.

[36] Lebedeva N, Boon-Brett L. Considerations on the chemical toxicity of contemporary Li-ion battery electrolytes and their components. J Electrochem Soc 2015;163:A821–A830.

[37] Ue M. Fire-resistant electrolyte for lithium battery JP1992–184870A; JP3274102B [in Japanese]. Japan: Mitsubishi Petrochem; 1992.

[38] Ue M, Sasaki Y, Tanaka Y, Morita M. Chapter 2: nonaqueous electrolytes with advances in solvents. Electrolytes for lithium and lithium-ion batteries. In: Jow

TR, Xu K, Borodin O, Ue M, editors. Modern aspects of electrochemistry. Springer; 2014.
[39] Lee CW, Venkatachalapathy R, Prakash J. A novel flame retardant additive for lithium batteries electrochemical and solid-state letters, Vol. 3; 2000, p. 63–5.
[40] Damen L, Lazzari M, Mastragostino M. Safe lithium-ion battery with ionic liquid-based electrolyte for hybrid electric vehicles. J Power Sources 2011;196:8692–5.
[41] Balducci A, Jeong SS, Kim GT, Passerini S, Winter M, Schmuck M, et al. Development of safe, green and high performance ionic liquids-based batteries (ILLIBATT project). J Power Sources 2011;196:9719–30.
[42] Kerner M, Lim D-H, Jeschke S, Rydholm T, Ahn J-H, Scheers J. Towards more thermally stable Li-ion battery electrolytes with salts and solvents sharing nitrile functionality. J Power Sources 2016;332:204–12.
[43] Paulechka YU, Kabo GJ, Blokhin AV, Vydrov OA, Magee JW, Frenkel M. Thermodynamic properties of 1-butyl-3-methylimidazolium hexafluorophosphate in the ideal gas state†. J Chem Eng Data 2003;48:457–62.
[44] Lemmon EW, McLinden MO, Friend DG . Thermophysical properties of fluid systems. In: Linstrom PJ, Mallard WG, editors. NIST chemistry WebBook, NIST standard reference database number 69. ⟨http://webbooknistgov⟩.
[45] Ohno H. Chapter 1: importance and possibility of ionic liquids. Electrochemical aspects of ionic liquids. New Jersey: John Wiley & Sons, Inc., Publication; 2005. p. 1–4.
[46] Daigle JC, Vijh A, Hovington P, Gagnon C, Hamel-Pâquet J, Verreault S, et al. Lithium battery with solid polymer electrolyte based on comb-like copolymers. J Power Sources 2015;279:372–83.
[47] Janek J, Zeier WG. A solid future for battery development. Nat Energy 2016;1:16141.
[48] Yamamoto H, Mori H. Chapter 7: SBR binder (for negative electrode) and ACM binder (for positive electrode). In: Yoshio Masaki, Brodd Ralph J, Kozawa A, editors. Lithium-ion batteries science and technologies. New York: Springer; 2009.
[49] Zhang Z, Ramadass P. Chapter 20: lithium-ion battery separators. In: Yoshio Masaki, Brodd Ralph J, Kozawa A, editors. Lithium-ion batteries science and technologies. New York: Springer; 2009.
[50] Yu WC, Hux SE. Method of making a trilayer battery separator. US Patent, 5,952, 120; 1999.
[51] Hying C. Separation separators for lithium batteries – safety & performance. Batteries. Paris; 2004.
[52] Pfrang A, Kriston A, Ruiz V, Lebedeva N, di Persio F. Chapter eight – safety of rechargeable energy storage systems with a focus on Li-ion Technology A2 – Rodriguez-Martinez, Lide M. In: Omar N, editor. Emerging nanotechnologies in rechargeable energy storage systems. Boston: Elsevier; 2017. p. 253–90.
[53] Kumar MS, Revankar ST. Development scheme and key technology of an electric vehicle: an overview. Renew Sustain Energy Rev 2017;70:1266–85.
[54] Arora S, Shen W, Kapoor A. Review of mechanical design and strategic placement technique of a robust battery pack for electric vehicles. Renew Sustain Energy Rev 2016;60:1319–31.
[55] Yeow K, Teng H, Thelliez M, Tan E. 3D thermal analysis of Li-ion battery cells with various geometries and cooling conditions using abaqus. In: Proceedings of the SIMULIA community conference; 2012, p. 1–16.
[56] Mikolajczak C, Kahn M, White K, Long RT. Lithium-ion batteries hazard and use assessment. In: Exponent failure analysis associates IFPRF, editor. Exponent Failure Analysis Associates, Inc., Fire Protection Research Foundation; 2011.
[57] Lamb J, Orendorff CJ. Evaluation of mechanical abuse techniques in lithium ion batteries. J Power Sources 2014;247:189–96.
[58] SAE J2289. Electric-drive battery pack system: functional guidelines; 2008.
[59] Lisbona D, Snee T. A review of hazards associated with primary lithium and lithium-ion batteries. Process Saf Environ Prot 2011;89:434–42.
[60] Spotnitz R, Franklin J. Abuse behavior of high-power, lithium-ion cells. J Power Sources 2003;113:81–100.
[61] SAE J2464. Electric and hybrid electric vehicle rechargeable energy storage system (RESS) safety and abuse testing; 2009.
[62] UN/ECE Regulation No. 100.02. Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train; 2013.
[63] UL 2580. Batteries for use in electric vehicles; 2013.
[64] Ashtiani CN. Analysis of battery safety and hazards' risk mitigation. 19th ed. Washington, DC; 2008, p. 1–11.
[65] Doughty DH, Crafts CC. SAND 2005–3123: freeDomCAR electrical energy storage systems abuse test manual for electric and hybrid electric vehicle applications; 2005.
[66] SAE J2929. Safety standards for electric and hybrid vehicle propulsion battery systems utilizing lithium-based rechargeable cells; 2013.
[67] ISO 12405-1. Electrically propelled road vehicles – test specification for lithium-ion traction battery packs and systems Part 1: high-power applications; 2011.
[68] ISO 12405-2. Electrically propelled road vehicles – test specification for lithium-ion traction battery packs and systems Part 2: high-energy applications; 2012.
[69] ISO 12405-3. Electrically propelled road vehicles – test specification for lithium-ion traction battery packs and systems Part 3: Safety performance requirements; 2014.
[70] IEC 62660-2. Rechargeable cells standards publication secondary lithium-ion cells for the propulsion of electric road vehicles Part 2: reliability and abuse testing; 2011.
[71] IEC 62660-3. Rechargeable cells standards publication secondary lithiumion cells for the propulsion of electric road vehicles Part 3: safety requirements of cells and modules; 2016.
[72] Unkelhaeuser T, Smallwood D. SAND99-0497-USABC: United States advanced battery consortium electrochemical storage system abuse test procedure manual; 1999.
[73] KMVSS Article18-3. Traction battery; 2009.
[74] AIS-048. Battery operated vehicles – safety requirements of traction batteries; 2009.
[75] QC/T 743. Lithium-ion batteries for electric vehicles Chinese voluntary standards for automobiles; 2006.
[76] UN 38.3; Recommendations on the transport of dangerous goods manual of test and criteria, 6th revised edition; 2015.
[77] ISO 16750-3. Road vehicles – environmental conditions and testing for electrical and electronic equipment Part 3: mechanical loads; 2003.
[78] UN/ECE Regulation No. 12. Uniform provisions concerning the approval of vehicles with regard to the protection of the driver against the steering mechanism in the event of impact; 2012.
[79] UN/ECE Regulation No. 94. Uniform provisions concerning the approval of vehicles with regard to the protection of the occupants in the event of a frontal collision; 2012.
[80] UN/ECE Regulation No. 95. Uniform provisions concerning the approval of vehicles with regard to the protection of the occupants in the event of a lateral collision; 2011.
[81] FMVSS 305. Electric powered vehicles: electrolyte spillage and electrical shock protection; 2011.
[82] Wisch M, Ott J, Thomson R, Léost Y, Abert M, Yao J. EVERSAFE. Recommendations and guidelines for battery crash safety and post-crash safe handling. In: Proceedings of the 7th framework programme era-net transport electromobility+; 2014.
[83] Adolph T, Edward M, Thomson R, Stein M, Lemmen P, V N, et al. FIMCAR full width test procedures: updated protocol in FIMCAR-frontal impact and compatibility assessment research , Bd VIII. Berlin: Universitatverslag der TU Berlin; 2015. p. 1–85.
[84] Dubaniewicz TH, DuCarme JP. Are lithium ion cells intrinsically safe? In: Proceedings of the industry applications society annual meeting (IAS). IEEE; 2012, p. 1–10.
[85] Maleki H, Howard JN. Internal short circuit in Li-ion cells. J Power Sources 2009;191:568–74.
[86] Cai W, Wang H, Maleki H, Howard J, Lara-Curzio E. Experimental simulation of internal short circuit in Li-ion and Li-ion-polymer cells. J Power Sources 2011;196:7779–83.
[87] Dubaniewicz TH, Jr., DuCarme JP. Further study of the intrinsic safety of internally shorted lithium and lithium-ion cells within methane-air. J Loss Prev Process Ind 2014;32:165–73.
[88] Spek EJ. Lithium ion abuse test methods improvement IEEE symposium on product compliance engineering (IEEE PSES). Portland, Oregon; 2012.
[89] Bierens JJLM. Handbook on drowning: prevention, rescue, treatment; 2006.
[90] Florida leads the nation in car crash drownings; 2014. ⟨http://touch.orlandosentinel.com/#section/-1/article/p2p-81915801⟩
[91] Hurricane sandy destroyed up to 250,000 cars; 2012. ⟨http://www.huffingtonpost.com/2012/11/07/hurricane-sandy-cars_n_2090916.html⟩
[92] Fisker loses over 300 karmas in sandy floods at Port Newark; 2012. ⟨http://www.autoblog.com/2012/11/07/fisker-loses-over-300-karmas-in-sandy-floods-at-port-newark/⟩
[93] Brecher A. Chapter 9: transit bus applications of lithium-ion batteries. In: Pistoia G, editor. Lithium-ion batteries: advances and applications; 2014, p. 194.
[94] Wech L, Richter R, Justen R, Schöneburg R. Crash safety aspects of HV batteries for vehicles. In: Proceedings of the international technical conference on the enhanced safety of vehicles ESV-22. Washington, USA; 2011.
[95] Bakker J, Sachs J, Otte D, Justen R, Hannawald L, Friesen F. Analysis of fuel cell vehicles equipped with compressed hydrogen storage systems from a road accident safety. Perspect SAE Int J Passeng Cars – Mech Syst 2011;4:332–42.
[96] Justen R, Schöneburg R. Crash SAfety of Hybrid and Battery Electric Vehicles. In: Proceedings of the international technical conference on the enhanced safety of vehicles ESV-22. Washington, USA; 2011.
[97] El-Hennawy HM, El-Menyar A, Al-Thani H, Tuma M, Parchani A, Abdulrahman H, et al. Epidemiology, causes and prevention of car rollover crashes with ejection. Ann Med Health Sci Res 2014;4:495–502.
[98] Baren JV. What is random vibration testing?. Sound Vib Instrum Ref Issue 2012:9–12.
[99] Jayahari L. Correlation of sinusoidal sweep test to field random vibrations [Master's degree thesis]. Karlskrona, Sweden: Blekinge Institute of Technology; 2005.
[100] Hooper JM, Marco J. Characterising the in-vehicle vibration inputs to the high voltage battery of an electric vehicle. J Power Sources 2014;245:510–9.
[101] IEC 60068-2-64. Environmental testing Part 2: test methods – test Fh: vibration, broad-band random (digital control) and guidance; 1993.
[102] SAE J2380. Vibration testing of electric vehicle batteries; 2009.
[103] ISO 6469-1. Electrically propelled road vehicles – safety specifications Part 1: on-board rechargeable energy storage system (RESS); 2009.
[104] ISO 6469-3. Electrically propelled road vehicles – safety specifications – Part 3: protection of persons against electric shock; 2011.
[105] ISO 6469-4. Electrically propelled road vehicles – safety specifications Part 4: post crash electrical safety requirements; 2015.
[106] ISO 17409. Electrically propelled road vehicles – connection to an external electric power supply – safety requirements; 2015.
[107] IEC 61851. Electric vehicle conductive charging system; 2010.
[108] ISO PAS 19363. Electrically propelled road vehicles – magnetic field wireless power transfer – safety and interoperability requirements.
[109] Wang Q, Ping P, Zhao X, Chu G, Sun J, Chen C. Thermal runaway caused fire and explosion of lithium ion battery. J Power Sources 2012;208:210–24.

[110] IEC 60898-1. Electrical accessories – circuit-breakers for overcurrent protection for household and similar installations Part 1: circuit-breakers for ac operation; 2015.
[111] Okazaki S, Higuchi S, Kubota N, Takahashi S. Measurement of short circuit current for low internal resistance batteries. J Appl Electrochem 1986;16:513–6.
[112] Conte FV, Gollob P, Lacher H. Safety in the battery design: the short circuit. World Electr Veh J 2009:3.
[113] Okazaki S, Higuchi S, Kubota N, Takahashi S. Predicted and observed initial short circuit current for lead-acid batteries. J Appl Electrochem 1986;16:631–5.
[114] UL 1642. UL standard for safety for lithium batteries; 2007.
[115] Mendoza-Hernandez OS, Ishikawa H, Nishikawa Y, Maruyama Y, Umeda M. Cathode material comparison of thermal runaway behavior of Li-ion cells at different state of charges including over charge. J Power Sources 2015;280:499–504.
[116] Wu A, Tabaddor M, Wang C, Jeevarajan J. Simulation of internal short circuits in lithium-ion cells. Corp Res UL LLC 2014.
[117] Zhao W, Luo G, Wang C-Y. Modeling internal shorting process in large-format Li-Ion cells. J Electrochem Soc 2015;162:A1352–A1364.
[118] Orendorff CJ, Roth EP, Nagasubramanian G. Experimental triggers for internal short circuits in lithium-ion cells. J Power Sources 2011;196:6554–8.
[119] IEC 62133-2. Secondary cells and batteries containing alkaline or other non-acid electrolytes – safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications - Part 2: Lithium systems; 2017.
[120] Jones HP, Chapin JT, Tabaddor M. Critical review of commercial secondary lithium-ion battery safety standards. European Space Agency, (Special Publication). In: Proceedings of the ESA SP 4th IAASS conference 'making safety matter'; 2010.
[121] Feng X, Fang M, He X, Ouyang M, Lu L, Wang H, et al. Thermal runaway features of large format prismatic lithium ion battery using extended volume accelerating rate calorimetry. J Power Sources 2014;255:294–301.
[122] Lu W, López CM, Liu N, Vaughey JT, Jansen A, DW D. Overcharge effect on morphology and structure of carbon electrodes for lithium-ion batteries. J Electrochem Soc 2012;159:A566–A570.
[123] IEC 61434. Secondary cells and batteries containing alkaline or other non-acid electrolytes – guide to designation of current in alkaline secondary cell and battery standards; 1996.
[124] Tobishima S, Sakurai Y, Yamaki J. Safety characteristics of rechargeable lithium metal cells. J Power Sources 1997;68:455–8.
[125] Xu F, He H, Liu Y, Dun C, Ren Y, Liu Q, et al. Failure investigation of LiFePO4 cells under overcharge conditions. J Electrochem Soc 2012;159:A678–A687.
[126] He H, Liu Y, Liu Q, Li Z, Xu F, Dun C, et al. Failure investigation of LiFePO4 cells in over-discharge conditions. J Electrochem Soc 2013;160:A793–A804.
[127] Zhang SS, Xu K, Jow TR. Study of the charging process of a LiCoO2-based Li-ion battery. J Power Sources 2006;160:1349–54.
[128] U.S. Environmental Protection Agency (EPA) method TO-15. Determination of volatile organic compounds (VOCs) in air collected in specially-prepared canisters and analyzed by gas chromatography/mass spectrometry (GC/MS); 1999. http://www.epa.gov/ttnamti1/files/ambient/airtox/to-15r.pdf.
[129] U.S. Environmental Protection Agency (EPA) method TO-17. Determination of volatile organic compounds in ambient air using active sampling onto sorbent tubes; 1999. https://www3.epa.gov/ttnamti1/files/ambient/airtox/to-17r.pdf.
[130] UN/ECE Regulation No. 34. Uniform provisions concerning the approval of vehicles with regard to the protection of fire risks; 2012.
[131] Lecocq A, Bertana M, Truchot B, Marlair G. Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle. In: Proceedings of the international conference on fires in vehicles – FIVE. Chicago, United States; 2012. p. 183–94.
[132] Andersson P, Blomqvist P, Lorén A, Larsson F. Investigation of fire emissions from Li-ion batteries. SP technical research institute of Sweden; 2013.
[133] Sturk D, Hoffmann L, AT A. Fire tests on e-vehicle battery cells and packs. Traffic Inj Prev 2015;16:159–64.
[134] Vimmerstedt LJ, Ring S, Hammel CJ. Current status of environmental, health and safety issues of lithium ion electric vehicle batteries. Golden, CO: National Renewable Energy Laboratory (NREL); 1995.
[135] Lebedeva N, Ruiz V, di Persio F, Kriston A, Pfrang A, Kosmidou T. et al. Evaluation of volume of free electrolyte in various cell types – method and preliminary results. EVS-07-24e – (JRC) free electrolyte. Working Party on Passive Safety (GRSP) – Electric Vehicle Safety (EVS) 7th session in ⟨https://www2.unece.org/wiki/display/trans/EVS+7th+session⟩; 2015.
[136] Roth EP, Orendorff CJ. How electrolytes influence battery safety. Electrochem Soc Interface 2012;21:45–9.
[137] Roth EP, Crafts CC, Doughty DH, McBreen J. Thermal abuse performance of 18650 Li-ion cells; 2004.
[138] Ohsaki T, Kishi T, Kuboki T, Takami N, Shimura N, Sato Y, et al. Overcharge reaction of lithium-ion batteries. J Power Sources 2005;146:97–100.
[139] Wargclou D. Extrication from cars during road traffic accidents. Swedish Civil Contingencies Agency (MSB); 2011.
[140] Casey C, Grant PE. Fire fighter safety and emergency response for electric drive and hybrid electric vehicles. Fire Prot Res Found 2010.
[141] Accident assistance and recovery of vehicles with high-voltage systems. German Association of the Automotive Industry (VDA); 2013.
[142] Emergency Response Planning Guidelines: ERPG level 2. ⟨https://www.aiha.org/get-involved/AIHAGuidelineFoundation/EmergencyResponsePlanningGuidelines/Documents/2014%20ERPG%20Introduction.pdf⟩.
[143] American industrial hygiene association. ⟨https://www.aiha.org/Pages/default.aspx⟩.
[144] Occupational safety and health administration (OSHA). ⟨https://www.osha.gov/⟩.
[145] Acute exposure guidelines levels from the environmental protection agency (EPA). ⟨http://www.epa.gov/oppt/aegl/pubs/chemlist.htm⟩.
[146] Short-term exposure limits (STEL). ⟨http://www.acgih.org/store/⟩.
[147] ASTM D4490. Standard practice for measuring concentrations of toxic gases of vapours using detector tubes; 2011.
[148] ASTM D4599. Standard practice for measuring concentrations of toxic gases of vapours using length-of-stain dosimeters; 2014.
[149] OSHA. Evaluation guidelines for air sampling methods utilizing spectroscopic analysis. ⟨https://www.osha.gov/dts/sltc/methods/spectroguide/spectroguide.pdf⟩.
[150] NIOSH. Manual for analytical methods. ⟨http://www.cdc.gov/niosh/docs/2003-154/⟩.
[151] IEC 62485-6. Safety requirements for secondary batteries and battery installations Part 6: lithium-ion batteries for traction applications PNW.

Glossary

ASTM: The American Society for Testing and Materials
CC: Constant Current
CV: Constant Voltage
ERPG: Emergency Response Planning Guidelines
EPA: Environmental Protection Agency
EV: Electric Vehicle
DUT: Device Under Test
BEV: Battery Electric Vehicle
FMVSS: Federal Motor Vehicle Safety Standards
HP: High Power
HE: High Energy
HEV: Hybrid Electric Vehicle
NIOSH: The National Institute for Occupational Safety and Health
NLF: New Legislative Framework
LIB: Lithium Ion Battery
OSHA: Occupational Safety and Health Administration
PSD: Power Spectral Density
STEL: Short-Term Exposure Limits
SOC: State of Charge
VOC's: Volatile Organic Compounds