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Glossary

Term	Definition
ASSB	All-solid-state battery
EV	Electric Vehicles
BEV	Battery Electric Vehicles
HEV	Hybrid Electric Vehicles
PHEV	Plug-in hybrid electric vehicles
NMC	Cathode combination of nickel-manganese-cobalt
LLZO	Ceramic electrolyte Li_7LaZrO_{12}
SEI	Solid-electrolyte interface
ESO	European Standardisation Organisations
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
ETSI	European Telecommunications Standards Institute
IEC	International Electrotechnical Commission
ISO	International Organisation for Standardisation

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IEEE SA	Institute of Electrical and Electronics Engineers Standards Association
BOG	Board of Governors at IEEE
JRC	Joint Research Centre at European commission
RoHS	Directive on restrictions of hazardous substances
UNECE	United Nations Economic Commission for Europe
EEE	Electrical and electronic equipment
DOE	U.S. Department of Energy.
BATSO	Battery Safety Organization.
REESS	REchargeable Energy Storage System
SOC	State of charge
CTE	Coefficient of thermal expansion
ICE	Internal combustion vehicle
BMS	Battery management system

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Abstract

In this deliverable we review the main regulations and standards related to Li-ion cells - i.e. regulatory requirement to facilitate international trade, to integrate the battery in electric and hybrid electric vehicle and regulation governing the transport of the battery cells and modules. This review sets up a short overview of minimum relevant regulation that need to be followed with the generation of all-solid-state cells and batteries including additional components for correct operation of the batteries (heating device, safety devices).

A short introduction to all solid-state batteries (ASSB) is given at the beginning of the deliverable focusing on the cathode and anode materials used ASSB and properties of such electrodes. Next, the proposed solid electrolyte materials are shortly discussed. Failure modes and safety aspects compared to liquid electrolyte Li-ion batteries are listed. Based on this failure modes relevant standards and regulations are described in terms of cell safety and abusive testing. The main standards that are discussed in further details are IEC 62660-2: 2018, UN/ECE-R100.02 and SAE J2464: 2009.

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1 Introduction

Thanks to the improvement in energy density of Li-ion technology materials in the recent decade, the market applications of Li-ion battery now also covers e-mobility, including EV/PHEV, electric buses, trucks and bikes. The sales of new EV's in EU have grown by 44% from 2018 to 2019 [1].

At present, lithium-ion cells of generation 1, 2a and 2b represent the core technology for electrical vehicle traction batteries (see Figure 1). These generations are expected to remain the chemistry of choice for at least the next 5 years. Current limitations of conventional lithium ion batteries (gen 1, 2a and 2b) are still somewhat limited energy density and particularly safety problems related to fire hazards and poisonous gasses discharge in case of a thermal runaway

Generation 3 is next to come, but the big game changer will likely happen with generations 4 (All-solid-state batteries) and 5 (lithium air batteries) both in terms of cost, performance and safety [2].

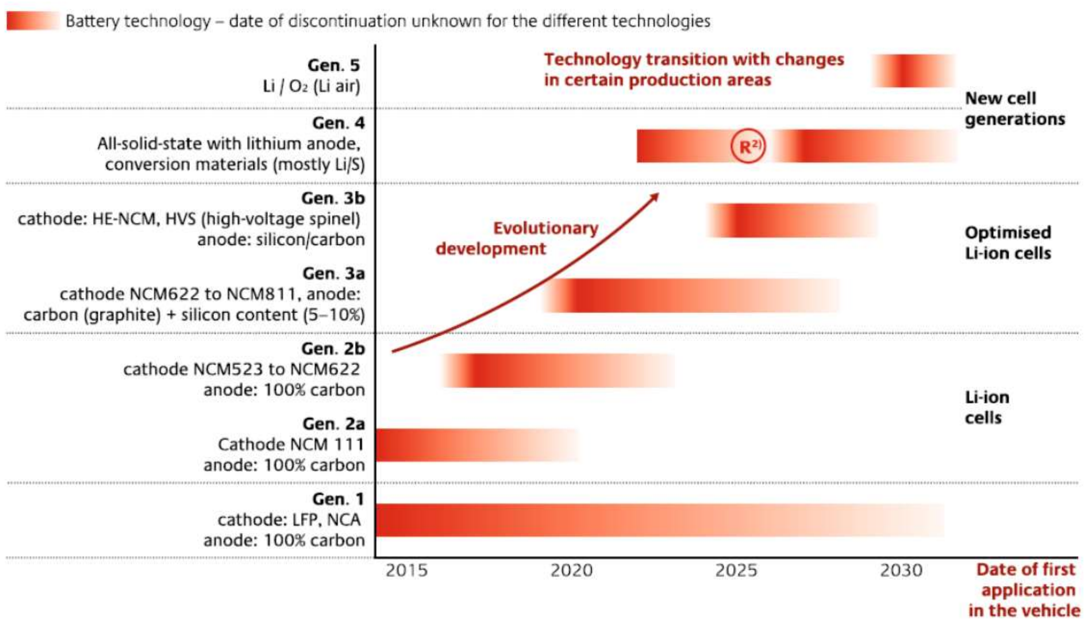

Figure 1: Classification of lithium-ion batteries based on cell generation. All-solid-state batteries are classified as generation 4 [2,3].

The focus of the ASTRABAT project is to accelerate the development of ASSB batteries in EU environment. The ASTRABAT project will develop a new generation of Li-ion battery to reach the targets of high energy density, safety and cost identified to reinforce social acceptance of electric vehicles and permit its market development. For this purpose, partners of ASTRABAT project will go beyond state of the art to deliver safe Li-ion battery, and reliable Li-ion cell [4]. It is a purpose of this deliverable to review the standards and regulation related to safety and international trade that could impact the development and production of ASSB within this project.

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2 Lithium battery safety aspects

The limitations of the lithium-ion batteries used in electric vehicles are well known. Most of the current commercialized lithium batteries employ liquid electrolytes, despite their vulnerability to battery fire hazards, because it is needed to avoid the formation of dendrites on the anode side [5]. Additionally, in lithium-ion batteries the Li^+ ion of the cathode dissolves, migrates and deposits to the anode side. It is part of this phenomenon, that contributes to the reduction of battery lifetime [6].
Safety systems on the battery pack level are needed to make sure the cells do not overheat and that the electrolyte does not ignite or explode. And to extend the electrode's lifetime, the battery must be cooled and prevented from ever fully charging or discharging, resulting in wasted capacity. All this adds bulk and cost [7].

All-solid-state batteries should display many advantages compared to lithium-ion batteries. Due to the lack of flammable organic components they should be inherently safer. In addition, they also should exhibit potential for a dramatic improvement in the energy density.

On the other hand, it is claim that the formation of dendrites is commonly not encountered in solid-state batteries. However, additional challenge of solid-state batteries is the lower ionic conductivity of the electrolyte. Therefore, extensive research efforts have been invested in the last few years to overcome this problem, the reward of which has been significant progress.

In addition to solid electrolytes, there are hybrid electrolytes like gel polymer (GPEs) with added some liquid electrolyte. Here function of added liquid is to improve conductivity and function of polymer material is to maintain good contact between electrode materials and the solid electrolyte. This represents a crucial function during battery operation when material volume changes due to thermal cycling [5].

2.1 ASTRABAT proposed electrolyte materials and their basic properties

One of main goals of ASTRABAT project is to develop all solid-state batteries which enable high energy density and obtain high durability. Main challenges in solid materials are linked with mechanical and chemical phenomena at the interface between solid electrolytes and electrodes.

The ceramic electrolytes such as LLZO (Li_7LaZrO_{12}) appear as promising solid electrolyte due to its electrochemical stability and good ionic conductivity (in range of 1 mS/cm) [8]. Stability window of LLZO electrolyte material, which is characterized as voltage range where electrolyte can sustain without redox decomposition, is sufficiently wide (6.4eV) to be used in all-solid-state cells with high voltage electrodes [9].

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On the way of integration of solid electrolyte into all solid-state battery cells there are some challenges that need to be tackled. Generally, failure modes originate either from mechanical processes (volume expansion, temperature expansion) or electrochemical processes (redox decomposition, other chemical reactions between electrolyte and electrode). On the other hand, some aging effects, such as transition metal dissolution that occurs with the liquid electrolyte are not expected in the solid-state cells [10].

In order to reduce interface resistance between electrodes and electrolytes, specific material and functionalization need to be introduced. Polymer materials are able to accommodate the volume change of the Si-based anode material. Then, the fluorocarbon based (at the cathode side) addresses the high voltage operation of the cathode material [11].

Among increased safety due to absence of flammable liquid advantage of solid electrolyte could also be longer lifetime (more than 10.000 cycles) and ability to operate at low and high temperature (-50 °C to 200 °C) in which conventional liquid electrolytes would freeze, boil or decompose [10].

2.2 ASTRABAT proposed electrode materials and their basic properties

NMC based composite is a suitable cathode material. These materials are characterized by high energy density and high voltage (>4 V) due to electric potential of metal ions such as Co^{4+} or Ni^{4+} [11]. On the anode side, silicon is a promising material that offers high theoretical capacity (3579 mAh/g) which is in the same range as lithium metal (3860 mAh/g). Silicon anodes are also less likely to develop dendrite growth than Li-metal anodes. Reduced dendrite growth makes silicon anodes a good potential material for new generation of batteries.

There are certain challenges to overcome also in electrode materials. In NMC materials self-heating may occur in case there is a local defect inside the cell or due to formation of the resistive solid-electrolyte interface (SEI) [12]. Self-heating causes increase of exothermic chemical reaction rate which may lead to thermal runaway [13]. The continuously rising temperatures during thermal runaway may result in battery combustion and explosions. Therefore, it is mandatory to drive batteries into thermal runaway by overheating tests under controlled conditions to understand all the potential risks, as detailed shown in [14].

Due to high cut off voltage NMC materials need to be combined with electrolyte which is stable at high voltage. Electrolytes have certain stability window specific to the material. Among two different materials which are suitable for cathodes NMC622 ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$) has cut off voltage at 4.2 V and NMC811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$) has cut off voltage at 4.5 V [11]. NMC811 is therefore less demanding in terms of choosing electrolyte material than NMC622, but on the other hand NMC811 faces with capacity fading and so require technological solution to tackle this issue.

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Silicon anodes are characterized by a large volume change during lithiation which leads to stress developed at contacts of solid particles. Stress induced crack propagation and delamination result in contact loss and temperature failures in NMC cathodes and such present possible failure mode.
Apart from temperature failure, gas evolution may appear at the cathodes when combined with solid state electrolyte [10].

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3 Legislative and standardization framework

This chapter describes existing regulations and standards framework relevant to electric vehicle battery with special focus on the all-solid-state battery safety as respect to the properties of the materials described in the previous chapter A short explanation of the hierarchy of relevant EU and international regulation is given. It identifies measuring and testing standards that need to be used in the compliance assessment of electric vehicle batteries in order the development of the battery with the aim to obtain CE mark and approval to put the ASSB on the market of EU.

It is necessary to differentiate between terms like regulation, legislation, standards, law and directives - these terms refer to the institution that creates them.

3.1 EU regulation

Regulations have binding legal force throughout every Member State and enter into force on a set date in all the Member States. On the other hand, a "directive" is a legislative act that sets out a goal that all EU countries must achieve. The individual countries have to incorporate into their own laws on how to reach these goals.
The directives are of most importance to bring goods to the European market. Every manufacturer has to decide what directives are valid for its products and to be in compliance with them. If directives are in vigour and they are followed, then the manufacturer can put CE marking on his product. However, since directives are not directly imposed on products, national laws and international standards should be followed [15].
The involved relevant regulation authorities for batteries are given below:

- the European battery directive
- the Clean vehicle Directive
- the Directive on restrictions of hazardous substances (RoHS)
- the UNECE vehicle regulation
- the General Product Safety Directive (covers Li-ion battery)
- the CE regulation

The relevant regulations are further described below.

3.1.1 European battery directive

Batteries commonly contain hazardous elements such as mercury, cadmium, and lead, which when incinerated or landfilled, present a risk to the environment and human health. Battery Directive (2006/66/EC), regulates the manufacture and disposal of batteries in the European Union with the aim of "improving the environmental performance of batteries and accumulators". All sealed batteries are covered by the Directive. The term “sealed” applies to most -if not all- types of batteries: Lead-acid, Nickel Cadmium (Ni-Cd), Lithium-Primary, Lithium-Ion (Li-ion), Zinc Alkaline, etc. It is interesting because it is applied for the topic of environmental impact and battery

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collection. Directive sets maximum quantities for certain chemicals and metals in certain batteries, tasks Member States with encouraging improvements to the environmental performance of batteries, requires proper waste management of these batteries, including recycling, collections, "take-back" programs, and disposal, sets waste battery collection rates, sets financial responsibility for programs and makes rules covering most phases of this legislation, including labelling, marking, documentation, reviews, and other administrative and procedural matters [16].

3.1.2 Clean vehicle Directive

The Directive on the Promotion of Clean and Energy Efficient Road Transport Vehicles aims at a broad market introduction of environmentally-friendly vehicles. It requires that energy and environmental impacts linked to the operation of vehicles over their whole lifetime are taken into account in all purchases of road transport vehicles, as covered by the public procurement Directives and the public service Regulation.
If the impacts are monetised for inclusion in the purchasing decision, common rules shall be followed for calculating the lifetime costs linked to the operation of vehicles. These rules are defined in the Directive [17].

3.1.3 Directive on restrictions of hazardous substances (RoHS)

EU legislation restricting the use of hazardous substances in electrical and electronic equipment (EEE) and promoting the collection and recycling of such equipment has been in force since February 2003. The legislation provides for the creation of collection schemes where consumers return their used waste EEE free of charge. The objective of these schemes is to increase the recycling and/or re-use of such products. The legislation also requires certain hazardous substances (heavy metals such as lead, mercury, cadmium, and hexavalent chromium and flame retardants such as polybrominated biphenyls or polybrominated diphenyl ethers to be substituted by safer alternatives) [18].

3.1.4 UNECE Electric vehicle regulation

The UNECE has developed the regulation **UNECE R100, Battery electric vehicle safety**, within committee ECE/TRANS/WP.2918. It concerns safety requirements for road vehicles with an electric power train and a maximum design speed exceeding 25 km/h. Type approval to UN ECE Regulation 100.02 is mandatory for the vast majority of new vehicle types in Europe. The Regulation covers electrical safety and consists of two parts:
Part I: Requirements of a Vehicle with Regard to its Electrical Safety
Part II: Requirements of a Rechargeable Electrical Energy Storage System (REESS) with Regard to Safety – test conditions for safety testing will be further described in chapter 5.

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This regulation comprises safety tests regarding vibration, thermal shock, mechanical shock, fire resistance and charge protection. It is applicable to complete battery systems and battery packs [15, 19].

3.2 EU and global standardization landscape & issuing bodies

Standards are not written by a government, but by public or private standardisation organisations. Typically, they refer to product performance or how to do a job, perform a test or measurement, and compliance with a relevant standard is a sign of god workmanship.
Standards are voluntarily, except if a specific standard is prescribed in a national regulation. If a certain standard is not followed, then a manufacturer must be able to justify to have taken a different route.
Standards for EVs have different scopes such as those addressing:

(1) the energy system itself;
(2) the application of the batteries, that is, the EV system;
(3) the interfaces between the EV and power grids; and
(4) the infrastructure.

In this division, standards in (1) centre on the isolated component, that is, the electrochemical cell, module, pack, or entire battery system, by measuring physical characteristics; those in (2) consider the system as a whole, including supporting control electronics, the cooling system, and its integration with the rest of the vehicle; those in (3) deal with communication and network interfaces between the EVs and the charging stations, the power grid, the wireless charger, or the supply equipment for bidirectional power flow; those in (4) describe the charging system from the energy utility point of view, electrified parking lots, energy transmission and management, and fire codes [20].

With development and adoption of the electric drivetrains for road vehicles a question needed to be answered is to which standardisation body would have the main responsibility for developing standards and for which of the above scopes. The electric vehicle represents in fact a mixed technology, being both a 'road vehicle' and an 'electrical device' [2].
By the end of the 1990s, a consensus was agreed defining the specific competences of the respective committees, ISO undertakes the work related to the vehicle as a whole (and develops standards at pack level), while IEC deals with the work related to electrical components and electric supply infrastructure (and develops standards at cell level) [21].

3.2.1 European Standards Organizations & Harmonised EU standards

A specific class of standards are the harmonised standards. The European Union directives, known as the "New Approach Directives", define "essential requirements" related to health, safety and environmental issues. Products must meet these requirements in order to be placed on the European market. European Commission can request the European Standardisation Organisations (ESOs) to develop and adopt

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European standards in support of European policies and legislations by issuing a standardisation request.
There are three European Standards Organizations:

- **CEN** (European Committee for Standardization),
- **ETSI** (European Telecommunications Standards Institute), and
- **CENELEC** (European Committee for Electrotechnical Standardization) Designated as a European Standards Organization by the European Commission, CENELEC is a non-profit technical organization set up under Belgian law, and is responsible for standardization in the electrotechnical engineering field. CENELEC prepares voluntary standards, which help facilitate trade between countries, create new markets, cut compliance costs and support the development of a Single European Market.
  CENELEC creates market access at European level but also at international level, adopting international standards wherever possible, through its close collaboration with the International Electrotechnical Commission (IEC), under the Frankfurt Agreement [22].

These organizations enable abovementioned essential requirements to be fulfilled through the path of harmonized European Standards.
Often CEN and CENELEC take over standards by the International Electrotechnical Committee (IEC) and the International Standards Organisation (ISO) and add clauses to bring the standards in accordance with the European rules on e.g. environmental protection, safety and consumer protection [15].

Manufacturers, other economic operators, or conformity assessment bodies can use harmonised standards to demonstrate that products, services, or processes comply with relevant EU legislation [23] (presumption of conformity, CE marking) and Member States must accept the free movement of such products.

When harmonised standards are not available, other types of (preferably international) standards may be considered to be brought to the level of harmonised standard through a legislative procedure [2].

3.2.2 International Electrotechnical Commission IEC

The International Electrotechnical Commission, founded in 1904, is a worldwide organisation for standardisation entrusted with all aspects in the electrotechnical field. Membership is required for all countries which are part of the World Trade Organisation (WTO) as commitment to remove international trade barriers, but it is open to all United Nations members [20].
The Technical Committees (TC), Sub-Committees (SC), of relevance in the field of battery related standards and electromobility within IEC are [24]:

- IEC TC 21 'Secondary cells and batteries'
- IEC TC 21/SC 21A 'Secondary cells and batteries containing alkaline or other nonacid electrolytes'

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- IEC TC 69 'Electric road vehicles and electric industrial trucks'
- IEC TC 21/PT 62984 'Secondary high temperature cells and batteries'
- IEC TC 35 ‘Primary cells and batteries’
- IEC JWG 69 Li. TC 21/SC 21A/TC 69 'Lithium for automobile/automotive
- applications'

3.2.3 International Organisation for Standardisation ISO

The International Organisation for Standardisation is a worldwide, independent, non-governmental international organization with a membership of 164 national standards bodies (ISO member bodies) [25]. It is committed to develop standards applicable worldwide in order to demolish barriers to the world trade. A standardisation process similar to that of IEC is followed in the development and revision of international standards. The TCs and SCs of relevance in battery related standards and electromobility are:

- ISO/TC 22 'Road vehicles'
- ISO/TC 22/SC 37 'Electrically propelled vehicles'
- ISO/TC 22/SC 38 'Motorcycles and mopeds' [26].

3.2.4 Institute of Electrical and Electronics Engineers IEEE SA

With a portfolio of nearly 1,300 standards and projects under development, IEEE is an important developer of industry standards in a broad range of technologies that drive the functionality, capabilities, and interoperability of products and services, transforming how people live, work, and communicate.
IEEE is governed by the Board of Governors (BOG) who are elected by IEEE SA Members. The Board of Governors oversees number of committees that are dedicated to manage key operational aspects of the IEEE SA. The IEEE SA Standards Board reports directly to the BOG, and oversees the IEEE standards development process [27].

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4 Standards related to EV battery performance and safety

Automotive traction batteries are assembled in levels, *i.e.* individual battery cells are connected in modules and modules are further connected to form a battery pack. In each standard a DUT level is specified. In Table 3 the level of test applicability is indicated for several selected standards as C: Cell, M: Module, P: Pack and V: Vehicle.

The intended application of the battery system is also sometimes referred to in the test standards. This application generally falls into two big groups. Typical application for the first group is in hybrid electric vehicles where the battery is subjected to short bursts of high current during charge and discharge, without the requirement to hold these states for a long time. In this first group the battery is used in conjunction an additional power source such as fuel cells and other power assisted vehicles. The battery is used here as an energy source to assist the vehicle during acceleration or cruising, or to absorb recoverable energy from the vehicle during braking. In the second group, the battery holds a large amount of energy and uses it in a mostly continuous fashion but at lower rates; this application corresponds to a battery electric vehicle (BEV) in which the battery is the only energy source for propulsion [20].

Table 1 lists battery performance related standards and Table 2 below lists safety related standards. The safety related standards list minimum required tests that the battery developed within the ASTRABAT project will have to pass before the cells can be transported or put on the market to be used in vehicles.

A good source of battery standards overview is also JRC technical reports such as '*Standards for the performance assessment of electric vehicles batteries and Light-duty vehicles emission testing*' [2]. This technical report also contains a description of Li-ion battery technology, standardization and regulatory landscape and analysis of functional battery parameters.

Table 1: List of relevant performance related standards.

	Current revision	Title of the standard	Org.
DOE/ID-10479	1996	USABC Electric Vehicle Battery Test Procedures Manual," United States Advanced Battery Consortium	DOE
IEC 62660-1	2018	Secondary lithium-ion cells for the propulsion of electric road vehicles—part 1: performance testing	IEC
IEC 61982	2012	Secondary batteries (except lithium) for the propulsion of electric road vehicles—performance and endurance tests	IEC
ISO 12405-4	2018	Electrically propelled road vehicles —Test specification for lithium-ion traction battery packs and systems — Part 4: Performance testing	ISO

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SAE J1798	2019	Recommended Practice for Performance Rating of Electric Vehicle Battery Modules	SAE
SAE J2288	2008	Life cycle testing of electric vehicle battery modules	SAE

Table 2: List of relevant safety related standards and manuals.

	Current revision	Title of the standard	Org.
BATSO 01	2013	Manual for Evaluation of Energy Systems for Light Electric Vehicle (LEV)—Secondary Lithium Batteries	BATSO
IEC/EN 62133	2017	Safety requirements on Li-cells and for batteries made for them: Part 2 Lithium systems	IEC
IEC 60086-4	2019	Safety of Lithium batteries	IEC
IEC 62660-2	2018	Secondary lithium-ion cells for the propulsion of electric road vehicles—part 2: reliability and abuse testing	IEC
ISO 6469-1	2019	Electrically propelled road vehicles — Safety specifications — Part 1: Rechargeable energy storage system (RESS)	ISO
ISO 16750-2	2012	Road vehicles — Environmental conditions and testing for electrical and electronic equipment — Part 2: Electrical loads	ISO
ISO 6469-3	2018	Electrically propelled road vehicles — Safety specifications — Part 3: Electrical safety	ISO
SAE J1766	2014	Recommended Practice for Electric, Fuel Cell and Hybrid Electric Vehicle Crash Integrity Testing	SAE
SAE J2380	2013	Vibration Testing of Electric Vehicle Batteries	SAE
SAE J2464	2009	Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing	SAE
SAE J2929	2013	Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells	SAE
UL 2271	2018	Standard for Batteries for Use In Light Electric Vehicle (LEV) Applications	UL
UL 2580	2016	Batteries for Use In Electric Vehicles	UL

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UN/ECE-R100.02	2013	Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train	UNECE
UN DOT 38.3	2019	UN manual of tests and criteria. Part III	UN

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5 Selected battery safety standards

In this chapter further description is given on a few selected standards concerning battery safety. We will focus on IEC 62660-2, ECE R100.02 and SAE J2464:2009. These standards have test conditions specified on cell, module and pack levels (see Table 3) and are therefore appropriate for assessment of cell prototypes developed during ASTRABAT project. ECE R100.02 also sets requirements for international trade while the standard SAE J2464:2009 is in-line with UN DOT 38.3 which is required before the batteries can be transported (to show that battery is safe and will not cause problem during *e.g.* air transportation). Additionally, the selected set of standards have been issued by both European and international standardisation bodies and offer good overall coverage.

5.1 IEC 62660-2:2018

IEC 62660-2:2018 specifies test procedures to observe the reliability and abuse behaviour of secondary lithium-ion cells and cell blocks used for propulsion of electric vehicles including battery electric vehicles (high energy density battery cells) and hybrid electric vehicles (high power density cells).
It also specifies the test procedures to obtain the essential characteristics of lithium ion cells for vehicle propulsion applications regarding capacity, power density, energy density, storage life and cycle life. These characteristics are indispensable for securing a basic level of performance and obtaining essential data on cells for various designs of battery systems and battery packs [28, 29, 30].

5.2 UN/ECE-R100.02

The manual applies to safety requirements with respect to the electric power train of road vehicles of categories M and N, with a maximum design speed exceeding 25 km/h, equipped with one or more traction motor(s) operated by electric power and not permanently connected to the grid. It also applies to their high voltage components and systems which are galvanically connected to the high voltage bus of the electric power train. This regulation does not cover post-crash safety requirements of road vehicles [19]. It provides description of electrical safety requirements, labeling, insulation resistance measuring methods, essential characteristics of Rechargeable Energy Storage Systems (REESS) and safety testing procedures.

5.3 SAE J2464:2009

Abuse test procedures in SAE J2464:2009 standard are intended to cover a broad range of vehicle applications as well as a broad range of electrical energy storage devices, including individual REESS cells (batteries or capacitors), modules and packs. This document applies to vehicles with REESS voltages above 60 volts. It does not apply to REESS that uses

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mechanical devices to store energy (e.g., electro-mechanical flywheels). The standard SAE J2464:2009 is in-line with UN DOT 38.3 [31, 32].
This standard is intended as a guide toward standard practice and is subjected to change to keep pace with experience and technical advances. It describes a body of tests which may be used as needed for abuse testing of electric or hybrid electric vehicle REESS to determine the response of such electrical energy storage and control systems to conditions or events which are beyond their normal operating range. The hazard severity level observed in the test is input to a risk management approach that combines severity and probability of occurrence to develop a hazard risk number for vehicular applications [33].

Table 3: Overview of safety and abuse tests levels in selected standards described in this chapter. Test level is indicated as C: Cell, M: Module, P: Pack and V: Vehicle [34].

Test		**IEC 62660-2: 2018**	**UN/ECE-R100.02**	**SAE J2464: 2009**
Mechanical	**Mechanical Shock**	C	C, M, P, V	C, M, P
	Drop			P
	Penetration			C, M, P
	Immersion			M, P
	Crush	C	C, M, P, V	C, M, P
	Rollover			M, P
	Vibration	C	C, M, P	
Electrical	**External short circuit**	C	C, M, P	C, M, P
	Internal short circuit	C		
	Overcharge/ overdischarge	C	C, M, P, V	C, M, P
Environmental	Thermal stability	C		C
	Thermal shock and cycling	C	C, M, P	C, M, P
	Overheat		C, M, P, V	M, P
	Fire		C, M, P, V	M, P

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5.4 Selected abuse and safety tests

There are several advantages of the all-solid-state batteries compared to Generation 1, 2a and 2b Lithium ion batteries as described in the Introduction chapter. These are:

- Non-flammable electrolyte,
- Increased energy density,
- Longer lifetime,
- No transition metal dissolution,
- Wider temperature operating range.

On the other hand, there also exist several challenges with the solid-state battery concept as described also in the literature [8-10]. These challenges are:

- Dendrite growth with non-Si anode,
- Large volume change of the Si anodes during lithiation and consequential anode to electrolyte delamination,
- Gas evolution from cathode,
- Redox decomposition.

During the ASTRABAT project duration several solid-state cell prototypes will be developed. These cell designs will have to be validated against the standard described in the preceding chapter before they can be put to market. The first test that one might do are those that test/prove the presumed advantages and solution to existing challenges of the ASSB batteries. In this respect the most relevant tests that will be described in further details are:

- Mechanical Shock
- Crush
- External short circuit
- Overcharge / overdischarge
- Thermal shock and cycling
- Fire

Other tests will not be further described here as their description is also available in the test standards themselves as well as Mat4bat deliverable 5.1 [15] and review by Ruiz *et al.* [34].

5.4.1 Mechanical Shock

During vehicle crash event the vehicle and with-it battery can be exposed to a mechanical shock of various degrees. With this test we are testing the robustness of the solid-state battery cell during such event. The shock forces are defined in terms of acceleration and shock duration representing different events from normal driving, high speed driving over kerbstone, to vehicle crash.
Table 4 below compares mechanical shock test conditions for cell level tests.

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Table 4: Mechanical shock testing conditions for selected standards at cell level [19, 28, 31].

	IEC 62660-2:2018	UN/ECE-R100.02	SAE J2464: 2009
Shock direction	Same direction as in vehicle driving direction	Lateral and transversal direction	Positive and negative directions. 3 repeats on 3 axes
Peak acceleration	51g	depends on the vehicle class. For vehicles <3.5t: 10g - 28g lateral and 4.5g – 15g in transversal	150g (m_c<0,5 kg), 50g (m_c>0,5 kg)
Shock duration	6 ms	80-120 ms	6 ms (m<0,5 kg), 11 ms (m>0,5 kg)
SOC	100 %	> 50%	95 – 100 % rated capacity

5.4.2 Crush

During the vehicle crash event substantial forces can occur acting on the battery enclosure or the cells themselves. Due to this forces the cell might deform. For the purpose of this test an electrically insulated plate – *(type A used for pack level)* or cylinder (for cylindrical cells) of halfsphere indenter (for prismatic and pouch cells) – (*type B used for cell level test)* -is pressed onto the battery until a certain compression is reached, before crush force reaches 1000 times the weight of the battery or if an abrupt drop of cell voltage is observed. Table 5 below compares crush test conditions for cell level tests.
Solid state batteries are assembled with comparatively thinner electrolyte layer relative to conventional (gen 1, 2a and 2b) lithium ion batteries. They also don't need the separator layer. This results in an important increase of the energy density of ASSB cells but at the same time puts the electrodes closer together and it is important to show that short circuit can be avoided during crush test.

Table 5: Crush testing conditions for selected standards at cell level [19, 28, 31].

	IEC 62660-2:2018	UN/ECE-R100.02	SAE J2464: 2009
Crush speed	/	/	0.5-1 mm/min
Crush force	<1000 m_c	100-105 kN	<1000 m_c
Crush plate type	B	A	B
SOC	80 %	> 50%	95-100 % rated capacity

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5.4.3 External short circuit

For this test execution a low resistance load (e.g. 5 mΩ) is placed between the terminals of the battery cell for a period of time (e.g. 10 min) -further details of the test are given in Table 6 below. The current flows through the cell and heats it up. With external short circuit test we evaluate the ability of the cell to withstand this current without reaching dangerous situation such as thermal runaway, fire or explosion. This test will also be a good indicator of the ability of the ASSB sells to avoid dendrite growth during rapid discharge. This test is very dependent on the SOC as high initial SOC will result in more severe conditions.

Table 6: External short circuit testing conditions for selected standards at cell level [19, 28, 31].

	IEC 62660-2:2018	**UN/ECE-R100.02**	**SAE J2464: 2009**
Cell cooling	/	/	Operational
Load resistance	<5 mΩ	<5 mΩ	Hard short: <5 mΩ Soft short: >10 mΩ
SOC	100 %	> 50 %	95 - 100%

5.4.4 Overcharge / overdischarge

Batteries on an electric vehicle are normally installed with an overcharge/overdischarge protection system. During battery charging the charger or Battery management system (BMS) can fail which can cause the battery cell to be overcharged. In order to test the protection system the cell is charged beyond the normal /recommended values set by the manufacturer according to some even to 200% SOC - further test details are given in Table 7.

On a cell level overcharge can lead to electrode breakdown or electrolyte decomposition. ASSB cells with Si anodes overcharge can lead to excessive anode volume expansion and hence anode-to-electrolyte interface delamination. At high level of overcharge the thermal runaway onset temperature is substantially lowered as compared to normal charge level. On the other hand, overdischarge can lead to formation of large dendrites and short circuit in the cell.

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Table 7: Overcharge / overdischarge testing conditions for selected standards at cell level. Passive overcharge and overdischarge protection device is operational during test while active protection is disabled [19, 28, 31]. This test answers question about battery safety in case of *e.g.* BMS fail.

	IEC 62660-2:2018	**UN/ECE-R100.02**	**SAE J2464: 2009**
Charge rate	5C (HEV) 1C (BEV)	> C/3 and < max normal operating current	1C constant current and max. regenerative current (3C)
End of charge	2 V_{max} reached or 200% SOC	until passive protection activates or 200% rated capacity	>200% or cell destruction
Discharge rate	1C	> C/3 and < max normal operating current	max recommended current
End of discharge	90 min	until passive protection activates or 25% nominal voltage	-100% SOC

5.4.5 Thermal shock and cycling

With this test one is evaluating the ability of the battery cell design to resist damage during rapid changes of ambient temperature, *e.g.* in aerospace applications. During the rapid and extreme changes of the ambient temperature the cell components will contract or expand and internal stress will occur between components with different coefficient of thermal expansion (CTE).
This test carries great relevance for the solid-state batteries as the solid electrolyte to electrode interface could delaminate. In some cases, small amount of liquid electrolyte is added which is aimed to improve and maintained electric contact between electrodes and the solid electrolyte during the thermal cycling and volume changes experienced during battery operation. This liquid addition is kept to a minimum in order to maintain the safety of the cell arising from inherit non-flammability of the solid electrolyte.
In most cases standards prescribe the higher temperature limit at +85°C and lower limit at -40°C, for further details see Table 8.

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Table 8: Thermal shock and cycling testing conditions for selected standards at cell level [19, 28, 31].

	IEC 62660-2:2018	UN/ECE-R100.02	SAE J2464: 2009
Thermal protection device	Disabled	Operational	Active controls disabled
T_{max}, T_{min}	+85°C, -40°C	+60°C, -40°C	+70°C, -40°C
Hold time	>90min and <110 min	6h	>1h
No. of cycles	30	5	5
SOC	80% (HEV) 100% (BEV)	>50%	95-100%

5.4.6 Fire test

With this test the objective is to assess the risk of explosion in case the battery is exposed to fire. Source of fire can be fuel spillage from an ICE vehicle or from the same vehicle if battery is installed in HEV or PHEV - for this reason in some standards this test is also called Exposure to simulated vehicle fire test. During the test the cell is placed in either a cylindrical fixture that is heated via an external radiant source - *radiant heat test* or by burning a fuel in a pan and placing the cell on a grating table above - *grating table test.* Further testing details are given in Table 9.
For the solid-state batteries this test is relevant as it showcases one of the main advantages over traditional Lithium ion batteries (gen 1, 2a and 2b). The ASSB batteries should perform significantly better at this test as no or minimal amount of flammable electrolyte is used.

Table 9: Fire testing conditions for selected standards at cell level. Fire test is not included in IEC 62660-2:2018 standard [19, 31].

	IEC 62660-2:2018	UN/ECE-R100.02	SAE J2464: 2009
Heat source	/	Flame	Radiant heat
Set-up	/	Grating table	Cylindrical metallic fixture
T_{max}	/	Not specified	890°C
Time at T_{max}	/	70 s	10 min
SOC	/	> 50% max operating SOC	100 %

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6 Conclusions

Solid-state batteries should be inherently safer when compared to conventional (generation 1, 2a and 2b) lithium ion batteries due to lack of flammable electrolyte at the same time they also provide higher energy density. They are therefore a much-anticipated new technology for use as traction battery technology of the near future. This said some challenging development still remain.

Battery safety standards were reviewed in this deliverable with focus on specific challenges associated to ASSB batteries described in Chapter 2. The most important safety test for solid state batteries are thermal shock and cycling tests and fast charge /discharge tests. First one to show that the ASSB design can maintain good electrical contact between electrode and electrolyte and the second to show that the ASSB cell can avoid dendrite growth during rapid discharge.

The presented list of standards and described tests is a minimum set that should be followed at least in order to showcase main advantages of ASSB and to test for main failure modes. This said, before the cells can be put to on the market a full compliance with regulation needs to be achieved and all the necessary tests in the relevant standards need to be performed.

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