Grant Agreement N°653373

SPICY Deliverable D6.1

Test protocols definition for WP6 (including critical review of protocols)

WP	6	Test and Li-ion, assessment
Task	1	Protocols and standardization

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[1] Dissemination level: **PU** = Public, **PP** = Restricted to other programme participants (including the JU), **RE** = Restricted to a group specified by the consortium (including the JU), **CO** = Confidential, only for members of the consortium (including the JU)

[2] Nature of the deliverable: **R** = Report, **P** = Prototype, **D** = Demonstrator, **O** = Other

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Deliverable abstract

VITO will evaluate the existing test protocols and standards. VITO will provide data related to the definition of several classes of usage profiles based on logging data (D6.1).

Based on the EV usage classes defined in WP1, suitable performance, ageing and abuse tests will be selected. Where needed new tests or adaptations of existing tests will be defined. CEA and TUM have already knowledge on ageing tests of Li-ion cell for EV application (projects SIMSTOCK, SIMCAL, MAT4BAT, ABatReLife, ExZellTUM, Pilebi), this expertise will be used to identify the best protocols. Selected test procedures and detailed description of all test procedures that will be used in this project are reported in (D6.1). The tests listed below could be performed from -20ºC to 50ºC:

- Charge and discharge cycles according to standards such as NEDC, DST, ...
- Charge and discharge continuous cycles until temperature stabilisation at different speed ranges. Maximum charge and discharge values to be defined depending on the reached temperature of the cell.
- Pulse charging and discharging, i.e. fast Pulse tests.
- Normalised charge and discharge.
- Normalised cycling tests until 4000 cycles at 80% DOD.
- Deep discharging (100% DOD).

In addition, based on its experiences, BeLife will provide its expertise on materials and cells testing to the partners to improve relevancy of testing protocols.

Deliverable Review

	Reviewer #1: Willy Porcher..................			Reviewer #2:		
	Answer	**Comments**	**Type***	**Answer**	**Comments**	**Type***
1. Is the deliverable in accordance with						
(i) the Description of Work?	☒ Yes ☐ No		☐ M ☐ m ☐ a	☐ Yes ☐ No		☐ M ☐ m ☐ a
(ii) the international State of the Art?	☒ Yes ☐ No		☐ M ☐ m ☐ a	☐ Yes ☐ No		☐ M ☐ m ☐ a
2. Is the quality of the deliverable in a status						
(i) that allows it to be sent to European Commission?	☒ Yes ☐ No		☐ M ☐ m ☐ a	☐ Yes ☐ No		☐ M ☐ m ☐ a
(ii) that needs improvement of the writing by the originator of the deliverable?	☐ Yes ☒ No		☐ M ☐ m ☐ a	☐ Yes ☐ No		☐ M ☐ m ☐ a
(iii) that needs further work by the Partners responsible for the deliverable?	☐ Yes ☒ No		☐ M ☐ m ☐ a	☐ Yes ☐ No		☐ M ☐ m ☐ a

* Type of comments: M = Major comment; m = minor comment; a = advice

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1. Introduction

Based on a review of existing standards dealing with lithium ion battery performance testing, a selection of the most relevant standards is made. As the Spicy project is focused on the automotive application, especially the plug-in-hybrid application, only the standards for EV application are analysed in this document. A summary of electric vehicle logging data is given in the second annex.

2. Performance testing

2.1. Characterization test

In the following is a selection of the main international lithium battery performances' testing standards for EV applications:

- IEC 62660-1 (performance testing for lithium-ion cells);
- ISO/DIS 12405-1 (lithium batteries for vehicles, high power applications);
- ISO/DIS 12405-2 (lithium batteries for vehicles, high energy application);
- DOE Battery test manual for plug-in hybrid electric vehicles (INL/EXT-07-12536).
- IEC 62620: Large format secondary lithium cells and batteries for use in industrial applications

IEC 62660-1:2010: Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 1: Performance testing

It specifies performance and life testing of secondary lithium-ion cells used for propulsion of electric vehicles including battery electric vehicles (BEV) and hybrid electric vehicles (HEV).

ISO 12405-1:2011: Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 1: High-power applications

ISO 12405-2:2012: Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 2: High-energy applications

ISO 12405-1& 2 specify test procedures for lithium-ion battery packs and systems for use in respectively high-power and high-energy applications.

The specified test procedures enable the determination of the essential characteristics of performance, reliability and abuse of lithium-ion battery packs and systems. They assist the user of ISO 12405-1:2011 to compare the test results achieved for different battery packs or systems.

Battery test manual for plug-in hybrid electric vehicles (revision3-september 2014): The DOE-United States Advanced Battery Consortium (USABC), Technical Advisory Committee (TAC) supported the development of the manual.

A short description of each characterization test of the above cited standards is presented in Table 1.

Table 1: Overview of battery characterisation test according to different standards

Application	**IEC 62660-1:2010**	**ISO 12405-1:2009**	**ISO 12405-2:2009**	Battery Test Manual For Plug-In Hybrid Electric Vehicles (Revision3- September 2014)
Capacity test	@ 0°C, 25°C and 45°C Discharge current (A)	@ 18°C, -10°C, 0°C, 25°C and 40°C Discharge current (A)	@ -25°C, -10°C, 0°C, 25°C and 40°C Discharge current (A)	According to manufacturer recommendations
	BEV: 1/3C **HEV:** 1C	1C 10C Imax	1/3C 1C 2C Imax	
Power test :	10sec pulse @ 20%, 50% and 80% SoC @ -25°C, 0°C, 25°C and 40°C Charge and discharge current (A) **BEV:** 1/3C; 1C; 2C; 5C; Imax **HEV:** 1/3C; 1C; 5C; 10C; Imax	several pulse duration @ 20%, 35%, 50%, 65% and 80% SoC @ -18°C, -10°C, 0°C, 25°C and 40°C Charge and discharge current (A) Imax (18s); -0.75Imax (10s)	several pulse duration @ 20%, 35%, 50%, 70% and 90% SoC @ -25°C, -18°C, -10°C, 0°C, 25°C and 40°C Charge and discharge current (A) Imax (18s); 0.75Imax (102s); -0.75Imax (20s)	Hybrid Pulse Power Characterization test: 10sec discharge pulse at Imax and 10sec charge pulse at 0.75Imax. @ each 10 % SoC from 90% 10% SOC with 1 hour rest.
BEV / HEV	Energy efficiency test @ 100% SoC and 70% SoC @ -20°C; 0°C; 25°C and 45°C Charge according to the manufacturer and rest 4 hours	Energy efficiency @ 0°; 25°C and 40°C @ 65%, 50 and 35% SoC 12s Charge pulse at Imax (or 20C) and rest 40s then 16s Discharge pulse at 0.75Imax (or 15C)		Energy efficiency 10s Charge pulses at maximum pulse current.
	BEV: Energy efficiency at fast charging @ 25°C Charge at 2C to 80% SoC and rest 4 hours Charge at 2C to 70% SoC and rest 4 hours		Energy efficiency at fast charging @ 25°C and 0°C Charge at 1C and rest 4 hours Charge at 2C and rest 4 hours Charge at Imax and rest 4 hours	
		No load SOC loss @ 25°C and 40°C @ 80% SoC No load for 24 hours; 168 hours;720 hours	No load SOC loss @ 25°C and 40°C @ 100% SoC No load for 48 hours; 168 hours;720 hours	Self-discharge test @ 30°C for 7 days
				Cold cranking: A pulse train of 2s pulses of either 5 or 7 kW at −30°C. The maximum DoD that still delivers the power has to be found.

Spicy Characterization test procedure:

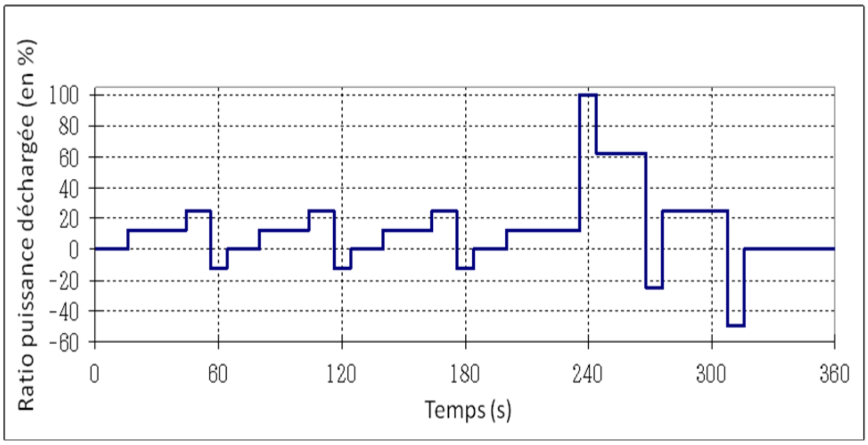
The characterization test is performed in the beginning-of-life of the battery. Based on the existing standards and on the different Spicy partners experience in battery testing (partners answers on the testing procedure questionnaire), here is the procedure for the characterization test (**to be discussed and approved by the Spicy partners**):

The following process should be performed @ 45°C, 25°C, 0°C, and -10°C.

Preconditioning: 2 standard cycles.

– Capacity test at different C-rates (C/20, 1C, 2C, yC)
  y in yC is the maximum continuous C-rate that is possible for all the cells.
  The 1C discharge is followed by a CV discharge until a C/20 current is reached.
  The cells are charged with the same rate as the discharge rate but limited to the maximally allowed continuous charging rate.

– Dynamic stress test (DST) (see profile below) to validate the battery model. It starts from 100% SoC to minimum voltage.



– Pulse test: 10sec discharge and charge pulses (charge balanced) @ 1C and yC @ 95%, 90%, 70%, 50%, 30%, 10%, 5% SoC.
  y in yC is the maximum pulse C-rate that is possible for all the cells.
  The charge pulse is limited to the maximally allowed pulse charge rate.

– Electrochemical impedance spectroscopic measurements @ 90%, 70%, 50%, 30%, 10%, 0% SoC.

Discussion elements:

- Should the proposed tests all be performed at the proposed temperatures?
- Is C20 good or can C25 be slow enough (this results in 10 h test time gain)?
- The max. discharge power in the DST test has to be defined. Proposition: make it relative to the cell size and average voltage: P_{max} = yC * Cell 1C capacity / U_{avg}
- Do we want to follow heating behaviour with a thermal camera?
- Do we want more pulse strengths in the pulse test?
- Do we need exact temperature control, e.g. 25±0,5°C, especially for EIS measurement?
- Is subzero (-10°C) charging is interesting to test? If yes at which C-rates?

Results that can be obtained from the proposed characterization test:

Capacity test:

- 1 C discharge capacity (Ah) and energy (Wh)
- Capacity (CC+CV(C20)) (Ah)
- yC discharge capacity (Ah) and energy (Wh)
- Discharge energy (Wh)
- Cycle efficiencies and Coulombic efficiencies
- Heating behaviour, especially at high C-rates
- SoC at which CV charging starts
- Discharge and charge profiles

Slow discharge capacity test (C20):

- Capacity (C20) in Ah and Wh
- Material ageing according to Incremental capacity analysis
- Material ageing according Differential voltage analysis
- Battery cell EMF based on averaging the discharge and charge profile

The following can be learned from the pulse test:

- Pulse efficiency
- (Cranking) power and internal resistance at 0,1 s; 1 s; 2 s and 10 s
- Pulse power density
- Voltage relaxation towards EMF
- Model parameterisation like FreedomCar model

The following can be learned from the Electrochemical Impedance Spectroscopic measurements:

- Internal battery dynamics can be identified like the double layer effect or the charge transfer reaction on electrode/electrolyte interface
- Fit of electrochemical models
- Follow up ageing behaviour of the model parameters

2.2. Ageing test

The ageing tests are designed to evaluate the battery performance degradation over time by charge and discharge cycles or by minimal usage. They are two kinds of ageing tests: the calendar life test (also called storage test) and the life-cycle test. The standards related to the use of lithium ion batteries in automotive application and describing the ageing tests are:

- **IEC 62660-1** (performance testing for lithium-ion cells);
- **ISO/DIS 12405-1** (lithium batteries for vehicles, high power applications);
- **ISO/DIS 12405-2** (lithium batteries for vehicles, high energy application);
- **DOE Battery test manual for plug-in hybrid electric vehicles** (INL/EXT-07-12536).
- **SAE J2288**: Life Cycle Testing of Electric Vehicle Battery Modules: This SAE Recommended Practice defines a standardized test method to determine the expected service life, in cycles, of electric vehicle battery modules. It is based on a set of nominal or baseline operating conditions in order to characterize the expected degradation in electrical performance as a function of life and to identify relevant failure mechanisms where possible.

A short description of these tests according to the standards is presented in respectively Table 2 and Table 3.

Table 2: Overview of life-cycle tests according to different standards

IEC 62660-1:2010	**BEV cycle-life** **Before cycling test:** - Capacity test @ 25°C - Dynamic discharge capacity test @ 25°C and 45°C - Power test @ 25°C @ 50% SoC **Life cycling:** @ 45°C 1- Cycling with the dynamic discharge profile A until the discharged capacity reaches equivalent to 50 % of the initial dynamic discharge capacity measured at 45°C. 2- Cycling with the dynamic discharge profile B 3- Cycling with the dynamic discharge profile A until the discharged capacity reaches equivalent to 80 % of the initial dynamic discharge capacity measured at 45°C. Repeat the test profile 28 days. Every 28 days perform periodical measurement of performance (same as the before cycling test only @ 25°C). **HEV cycle-life test** **Before cycling test:** - Capacity test @ 25°C - Power test @ 25°C @ 50% SoC **Life cycling:** @ 45°C 1- Cycling with the discharge-rich profile from 80% SoC to 30% SoC 2- Cycling with the charge-rich profile from 30% SoC until 80% SoC 3- Repeat the test for 22 hours then rest for 2 hours Every 7 days perform power test @ 25°C @ 50% SoC Every 14 days, perform capacity test End of test after 6 months or the performances decreased less than 80%.
ISO 12405-1:2009	Before cycling: 1C capacity test @ 25°C @ 25°C Cycling by the discharge-rich until SoC 30% then cycling by the charge-rich profile until SoC 80% for 22 hours then rest 2 hours. Repeat the test 7days Every 7 days: pulse test Every 14 days: 1C capacity test and pulse test
ISO 12405-2:2009	C/3 capacity test @ -10°C and 25°C @ 25°C From 100% to 20% SoC Dynamic discharge profile A + Dynamic discharge profile B + Dynamic discharge profile A Repeat the test 28 days Every 28 days: C/3 capacity test and pulse power @ 25°C Every 2 months: C/3 capacity test and pulse power @ -10°C and 25°C
Battery Test Manual For Plug-In Hybrid Electric Vehicles (Revision3- September 2014)	Charge-Sustaining Cycle Life Tests: It is based on the energy efficiency test profile. It takes 9 s. It is repeated for 7500 h being 300k cycles, transferring 15 MWh. It can be scaled to module and cell level. It is performed at a certain, not pre-defined SOC. The profile depends on the target size of the battery: minimum, medium and maximum PHEV battery. The discharge pulse is 27 kW during 3 s for the minimum size and 23 kW for the

	maximum size. If the pulses reach the voltage limits before the 300k cycles then it is end of test. Charge depleting cycle life test It is based on a 360 s profile with a 50 kW, 2 s discharge pulse and a 30 kW, 2 s charge pulse for the minimum battery size. It reduces to 46 kW discharge pulse and 25 kW charge pulse for the maximum size. The profile is repeated around 7 times, removing 3.4 kWh for the minimum battery size and around 25 times, removing 11.6 kWh for the maximum battery size. After this, the battery is recharged to certain, undefined, SOC. This is repeated for 5000 cycles. It corresponds to 29 MWh for the minimum and 58 MWh for the maximum battery size
SAE J2288	Discharge to 80% DoD with the dynamic capacity test (SAE J1798) then full charge. Repeat the test 28 days Before cycling and every 28 days, the following measurement shall be performed: 1- Capacity Test at the C/3 constant current rate as defined in SAE J1798. 2- A Dynamic Capacity Test to a maximum of 100% of rated capacity as defined in SAE J1798. 3- A Peak Power Test as defined in SAE J1798 End-of-life limit: a- The measured capacity (either static or dynamic) is less than 80% of rated capacity, or, b- The peak power capability is less than 80% of its rated value at 80% depth-of-discharge

Table 3: Overview of calendar tests according to different standards

IEC 62660-1:2010	**Charge retention test** @ 45°C @ 50% SoC Capacity test every 28 days **Storage life test** **Before cycling** - Capacity test - Power density test - Regenerative power test **Calendar life:** @ 45°C @ 100% SoC for BEV and 50% SoC for HEV The 'Before cycling test' is performed every 42 days. The complete procedure is repeated 3 times.
ISO 12405-1:2009	**SoC loss at storage** @ 45°C @ 50% SoC for 30 days The remaining capacity is measured by a 1C discharge test.
ISO 12405-2:2009	**SoC loss at storage** @ 45°C @ 50% SoC for 30 days The remaining capacity is measured by a C/3 discharge test.
Battery Test Manual For Plug-In Hybrid Electric Vehicles (Revision3-September 2014)	Calendar life test @ 100% SoC or a target SoC @ at least 3 different temperatures A pulse profile is executed every 24 hours. A reference performance test is applied every 32 days. It consists of a 10kW constant power discharge test and a HPPC test.
SAE J2288	SAE J2288 is only dealing with life cycling

Spicy ageing test procedure:

The answers provided by the Spicy partners related to the ageing test questionnaire will be synthesized in the deliverable D6.2.

The questionnaire is attached in the annex of this deliverable.

3. Reliability and abuse testing

3.1. Reliability and abuse tests in the standards

Standards have been developed for reliability and abuse tests of batteries for electric vehicles and particularly for Li-ion cells. Both test types are in principle destructive tests, to be sure that no dangerous situations could occur in real life. If the result is really destructive and to which degree, that depends on the quality of the cells and the battery made with them. The difference between reliability tests and abuse tests is small. The first are conditions that should resemble real life behaviour whereas the second is not anymore real life but about foreseeable misuse. UN38.3 classifies the crush test as a mechanical abuse test, leaving it almost open if it is a reliability or an abuse test. Since it is a test for transporting cells and batteries it can be considered dealing with reliability. In IEC 62660-2 it has been formulated more clearly as a reliability test: ‘This test is performed to characterize cell responses to external load forces that may cause deformation’. However, this standard makes no distinction between abuse tests and reliability tests although these categories are in its title. In standard IEC 62619 all tests directly on cells are considered as misuse tests.

IEC 62660-3 makes a division even more difficult. This standard is about safety tests although it uses the same test set-ups as in its brother standard part 2, reliability and abuse tests. Many tests are identical and if they differ then it is mainly with easier test conditions. SAE J2929 calls their tests also safety tests considering the same test subjects as the standards mentioned before. Standard IEC 62619 however contains a section on safety tests that is different. They all belong to testing the battery management system in connection with the battery to verify that it works correctly. In the standard UL 2580 and in regulation UNECE R100 Annex 8 these tests are called protection tests. The ‘FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications’ ((DOE) SAND2005-3123) use a classification of three abuse levels.

Concluding, it is not important to try to make a difference between abuse, reliability and even safety and protection tests since the criteria seem arbitrary and changing from standard to standard. In this document, all these tests are taken into account.

Over 100 standards exist for electric vehicle application. To find the standards that include safety testing and safety requirements, an appropriate tool is to use the website ‘batterystandards.vito.be’. It gives the worldwide available standards on Li-ion batteries and system integration with them. It tries to be as up to date as possible. The list that is found in this way can be filtered further by omitting standards that do not cover Li-ion batteries or are specifically meant for stationary or portable application. At the end 28 standards seem to be of interest for the Spicy project. The result is given in Table 4 and Table 5. The first table is split in two sections: standards that are applicable on Li-ion cells and on (Li-ion) batteries for electric vehicles. The second table is of secondary interest since the standards here become further away from the Spicy objective. Three sections are given: Li-ion batteries for light weight vehicles, standards on electric vehicle level and rules that need to be followed to transport batteries by air plane, train, lorry and ship.

In the tables, general information is provided on the standards. It is given who made them, on which level they are applicable (world, continent, country, private). UL standards have been indicated here as ‘continent’ since they are extensively used in the United States and

Canada. Strictly speaking these are standards of a private organisation that can be used in other regions as well. The application is given in the tables. This can be for batteries in general or for (L) EV batteries in specific or very broad, i.e. for transport means. The life phase is given (design, transport, use) and finally the title of each standard.

Table 4: Overview of standards applicable for Li-ion batteries in electric vehicle application.

Editor	Geography	Reference	Year	Application	Battery or application type	Life phase	Title
Li-ion cells and packs that can be used for EV							
United Nations	World	UN38.3	N.A.	battery	Li-ion	transport	UN Manual of Tests and Criteria, 4th Revised Edition, Lithium Battery Testing Requirements
IEC, CENELEC	World	IEC/EN 62281	2013	battery	Li-ion	transport	Safety of primary and secondary lithium cells and batteries during transport
IEC, CENELEC	World	IEC/EN 62660-2	2010	EV	Li-ion	use	Secondary batteries for the propulsion of electric road vehicles - Part 2: Reliability and abuse testing for lithium- ion cells
IEC	World	IEC 62660-03 NWP	under development	EV	Li-ion	use	Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 3: Safety requirements
IEC	World	IEC 62619	under development	battery	Li-ion	design, use	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for large format secondary lithium cells and batteries for stationary and motive applications
UL	Continent	UL 1642	2012	battery	Li-ion	use	UL Standard for Safety of Lithium Batteries (primary and secondary cells)
Japanese battery association	Country	SBA S1101	2011	battery	Li-ion	use	産業用リチウム二次電池の安全性試験
Ellicert	Private	Ellicert Battéries	2012	EV	Li-ion	design, use	Certification scheme for battery cells and packs for rechargeable electric and hybrid vehicles – General requirements relating to certification – Application to Lithium based elements
(Li-ion) batteries that can be used for EV							
ISO	World	ISO 12405-1	2011	EV	Li-ion	use	Electrically propelled road vehicles - Test specification for lithium-ion traction battery packs and systems - Part 1: High-power applications
ISO	World	ISO 12405-2	2012	EV	Li-ion	use	Electrically propelled road vehicles - Test specification for lithium-ion traction battery packs and systems - Part 2: High-energy applications
ISO	World	ISO/DIS 12405-3	under development	EV	Li-ion	use	Electrically propelled road vehicles - Test specification for Lithium-ion traction battery packs and systems - Part 3: Safety performance requirements
UNECE	Continent	UNECE R100 Annex 8	2010	EV	batteries	use	Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train – REESS test procedures
UL	Continent	UL2580	2011	EV	batteries	use	Batteries for use in electric vehicles
SAE	Country	SAE J2929	2011	EV	Li-ion	use	Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells
SAE	Country	SAE J2464	2009	EV	batteries	design, use	Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
US DoE	Country	(DOE) SAND2005-3123	2005	EV	batteries	design, use	FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications
VDA	Private	VDA	2008	HEV	Li-ion	design, use	Test Specification for Li-Ion Battery Systems: Test Specification for Li-Ion Battery Systems for HEVs

Table 5: Overview of standards of secondary interest, applicable for Li-ion batteries in electric vehicle application.

Editor	Geography	Reference	Year	Application	Battery or application type	Life phase	Title
Li-ion batteries that can be used for LEV							
ISO	World	ISO 18243	under development	LEV	Li-ion	design	Electrically propelled mopeds and motorcycles -- Test specification and safety requirements for lithium-ion battery system
CENELEC	Continent	prEN 50604-1	under development	LEV	Li-ion	use	Secondary lithium batteries for LEV (Light Electric Vehicle) applications - Part 1: General safety requirements and test methods
UL	Continent	UL 2271	N.A.	EV	batteries	use	Batteries For Use in Light Electric Vehicles
BATSO	Private	BATSO 01	2011	EV	Li-ion	use	Manual for evaluation of energy systems for Light Electric Vehicle (LEV)- Secondary Lithium Batteries
Vehicle level							
UNECE	Continent	UNECE R100	2010	EV	batteries	use	Battery electric vehicle safety
ISO	World	ISO 6469-1	2009	EV	storage	use	Electrically propelled road vehicles - Safety specifications - Part 1: On-board rechargeable energy storage system (RESS)
SAE	Country	SAE J1766	under development	EV	batteries	use	Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing
China	Country	GBT 18384.1	2001	EV	batteries	N.A.	Electric vehicles--Safety specification--Part 1: On-board energy storage
Transport of (Li-ion) batteries							
IATA	World	IATA DGR	2013	goods	transport	transport	Dangerous goods regulations (DGR, 54th edition)
IMO	World	IMDG	2010	goods	transport	transport	International Maritime Dangerous Goods (IMDG) Code
UNECE	Continent	ADR	2011	goods	transport	transport	European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR)
OTIF	Continent	RID	2012	goods	transport	transport	International Convention concerning the carriage of Goods by Rail, Annex 463 A: International regulations concerning the carriage of dangerous goods by rail (RID)

The standards mentioned in Table 4 will be explored in more detail. The Japanese standard is not available in English, so this one must be skipped. From the second section VITO is not in possession of SAE 2464. The VDA standard is specifically for hybrid electric vehicle application and therefore of less interest. The standards that remain to be investigated are:

- Cells and packs that can be used in EV application:
  UN38.3, IEC/EN 62281, IEC/EN 62660-2, IEC 62660-03 NWP, IEC 62619, UL 1642, Ellicert Battéries
- (Li-ion) batteries that can be used for EV:
  ISO 12405-1, ISO 12405-2, ISO/DIS 12405-3, UNECE R100 Annex 8, UL2580 , SAE J2929, (SAE J2464 (not possessed)), (DOE) SAND2005-3123

Strictly speaking UN38.3 and UNECE R100 Annex 8 are no standards but regulation. Ellicert Battéries is a certification scheme. All these three cover test procedures for reliability and abuse testing. In this document all of them will be referred to as standards for ease.

Table 6 gives the tests that are found in the identified standards. This appears to be 29 tests. They have been assembled in four categories being ‘mechanical’, ‘thermal’, ‘electrical’ and ‘environmental’. The first three categories are often used in the standards but a specific test may be ranked in another category then here is done. No standard uses the category ‘environmental’. This class represents influence from outside the battery different from mechanical, thermal or purely electrical. It appears that the standards have quite some differences in the tests that they address. Also a large difference exists in the number of tests. UL2580 and (DOE) SAND2005-3123 contain the largest number of tests, both 16. From the second section only (DOE) SAND2005-3123 contains tests that may be applied at cell level.

The standards on Li-ion cells and batteries (first section) are rough in classifying a battery. They indicate cells, cell-blocks and the battery. A cell-block consists of cells that are placed in parallel to become a higher capacity. The standards of the second section consider more levels between cell and complete system like module and pack. The standards use different wording for these levels. In the first section of the table (Li-ion cells and packs that can be used for EV) tests that cover cell level are simply indicated by an ‘x’. In the second section (Li-ion batteries that can be used for EV) the application is given in words. As said, only one standard contains some tests that may be performed at cell level.

Looking at all tests it appears that 17 can be applied on cells. Most important is the UN38.3 regulation. The described tests have to be fulfilled to be able to transport cells and batteries. It has 8 tests. One test (overcharge) is only applicable to batteries. If the cell is smaller than 20 mm in diameter an impact test is performed, else a crush test. Therefore, it results in 9 tests in the sum at the bottom of the table.

The other standards are not obligatory. It has to be known what test conditions are given. Maybe all tests are almost the same. A short indication of the test conditions is given in Table 7.

Table 6: Tests that are given in the identified standards. If they cover cell level then an 'x' is set in the first section, else the applicable level is given. In the second section always the level is given since these standards are not made for cell level, but some can be used at cell level.

	Li-ion cells and packs that can be used for EV							**Li-ion batteries that can be used for EV**							
Test topic \ Standard	UN38.3	IEC/EN 62281	IEC/EN 62660-2	IEC 62660-03 NWP	IEC 62619	UL 1642	Ellicert Batteries	ISO 12405-1	ISO 12405-2	ISO/DIS 12405-3	UL2580	SAE J2929	*SAE J2464*	(DOE) SAND2005-3123	UNECE R100 Annex 8
Mechanical															
Vibration	x	x	x			x	x	subsystem, pack, system	subsystem, pack, system		module, system	at least subsystem			module or higher
Mechanical Shock	x	x	x	x		x		pack, system	pack, system	pack, system, vehicle	system	battery or vehicle		module	module or higher
Drop		filled package box			x		battery				system	battery		pack	
Impact	x	x			x	x	x								
Crush (mechanical integrity)	x	x	x	x		x	x			pack, system, vehicle	system	battery or vehicle		module	module or higher
Penetration							x							cell or higher	
Roll-over											system			module	
Thermal															
Temperature cycling (shock)	x	x	x	x		x	x	pack, system	pack, system	pack, system		battery		cell or higher	module or higher
High temperature endurance			x	x	x	x	x				system			cell or higher	
Thermal control check					battery					pack, system	system	battery			module or higher
Fire exposure						x	battery			pack, system	module, system	battery		module	module or higher
Propagation of thermal runaway					battery						module, system				
Rapid charging and discharging											module, system			module	
Thermal stability (ARC)														cell or higher	
Electrical															
External short circuit	x	x	x	x	x	x	x	pack, system	pack, system	pack, system	pack, system	battery		module (2 tests)	module or higher
Internal short circuit				x	x										
Overcharge	battery	battery	x	x	x	x	x				system			module	
Forced discharge	x	x	x	x	x	x	x							module (2 tests)	
Imbalanced charge											system				
Overcharge voltage control check					battery			system	system	pack, system		battery			module or higher
Overcharge current control check					battery										
Over-discharge current control check								system	system	pack, system	at least module	battery			module or higher
Environmental															
Altitude simulation	x	x				x	x								
Humidity												battery			
Dewing								pack, system	pack, system	pack, system					
Immersion / Flooding							battery			not specified	module, system	battery			
Salt spray / salt water immersion											module, system			cell or higher	
Rain test															
Electromagnetic susceptibility												battery			
Number of tests	9	10	8	8	11	11	13	7	7	10	16	13	–	16	9

It appears that some tests are close to other ones. Standard IEC 62281 is close to UN 38.3. It comprises three sections: transport tests, packaging test and safety information on packaging and transporting batteries. The transport tests use the same test clauses as found in UN38.3 and have the same test conditions. The packaging test is not on cell level, but is carried out with a box full of cells or batteries like they are transported.

The tests in 62660-3 (safety of Li-ion cells in electrical road vehicles) are often the same as in IEC 62660-2 (reliability and abuse tests). If they differ then the conditions in part 3 are easier than in part 2. Part 3 has an internal short circuit test that is not included in part 2.

The test set-ups and conditions of IEC 62660-2 are often quite different from UN38.3. It is difficult to estimate if one is more severe than the other. For example the short circuit test in UN38.3 can be performed with much lower current, but at elevated temperature and for a long period, whereas in IEC 62660-2 it is maintained only for 10 min. The crush test in the latter is with help of a bar or a hemisphere allowing a maximal deformation of 15%, whereas UN38.3 crushes between plates, allowing a maximal deformation of 50%.

Most short circuit tests create hardly a high current for large cells according to the test conditions. Cells of 2Ah have typically a resistance of 10 mOhm whereas cells of 10 Ah have a typical resistance of 2 mOhm (see G. Mulder e.a. , ‘Comparison of commercial battery cells in relation to material properties’, Electrochimica Acta, 2013, figure 8D). If an external resistance of 100 mOhm is used, this results approximately into 40A or 20 C for a small cell but only 4 C for a 10 Ah cell. The test condition of IEC 62660-2 is with 5 mOhm much harder, but is confined to 10 min. as was stated above.

Table 7: Short indication of the contents of the tests applicable at cell level. Tests that do not exist at cell level are greyed out. (The table covers two pages).

Test topic \ Standard	UN38.3	IEC/EN 62281	IEC/EN 62660-2	IEC 62660-03 NWP	IEC 62619	UL 1642	Ellicert Battéries	(DOE) SAND2005-3123
Mechanical								
Vibration	7-200Hz, 12h, 1 to 8g_n	acc. UN38.3	10-2000Hz, 24h, 27,8 m/s^2			10-55Hz, 0.8mm, 95 min.	acc. UN38.3	
Mechanical Shock	150 g_n half sine of 6ms, 18x(cell)	acc. UN38.3	500m/s^2 half sine of 6ms, 30x(cell)	acc. Part2		shock from 75 to 150g_n, 3X	acc. IEC62660-2	(module)
Drop		(package box)			drop from 100cm		(battery)	(pack)
Cell impact	a bar on the cell, falling weight of 9kg, 60cm	acc. UN38.3			close to UN38.3	close to UN38.3		
Crush	crushing surfaces with 1,5cm/s until 13kN, 50% deformation or 100 mV voltage drop	acc. UN38.3	crushing bar or sphere, until 1000X cell weight, 15% deformation or voltage drop of 1/3 of V_{init}	acc. Part2, speed <6mm/min.		crushing surfaces with 1,5cm/s until 13kN	acc. IEC62660-2	(module)
Penetration							acc. SAE J2464	3mm steel rod with 8cm/s
Roll-over								
Thermal								
Temperature cycling	-40 to 72°C, 10X	acc. UN38.3	-40 or $T_{min\ from\ manufacturer}$ to 85°C or $T_{max\ from\ manufacturer}$, 30X, wit or without electrical operation	acc. Part2		close to UN38.3	acc. UN38.3	-40 to 80°C cycling, 5X
High temperature endurance			130°C, 30 min.	acc. Part 2, 6h observation	85°C, 3h	≥130°C, ≥10 min., depending on cell's temperature specification	acc. SAE J2464	storing in 40, 60 and 80°C until 20% capacity decrease
Thermal control check					(battery)			
Fire exposure						cell in flame until explosion or burn-out	(battery)	(module)
Propagation of thermal runaway					(battery)			
Rapid charging and discharging								(module)
Thermal stability (ARC)								30 to 200°C above operational temp. until self-heating

Test topic \ Standard	UN38.3	IEC/EN 62281	IEC/EN 62660-2	IEC 62660-03 NWP	IEC 62619	UL 1642	Ellicert Battéries	(DOE) SAND2005-3123
Electricity								
External short circuit	<0,1 Ohm @55°C, >1h	acc. UN38.3	<5mOhm, 10 min.	acc. Part2	30 mOhm, 6h	80mOhm until 0,2V	acc. IEC62660-2	(module)
Internal short circuit				several methods, preferably an inserted nickel particle	insertion of nickel particle			
Overcharge	(battery)	(battery)	$1I_{t\,(BEV)}$ or $5\,I_{t\,(HEV)}$ until 200% SOC equivalent or 2X Vmax	$1I_{t\,(BEV)}$ or $5\,I_{t\,(HEV)}$ until 1,2 X V_{max} or 130% SOC equivalent	charge until max. voltage of charger that lost control, except if double protection is used.	3X $I_{max.\ charge\ by\ manufacturer}$, for 7h or reaching end of charge condition by manufacturer	acc. IEC62660-2	(module)
Forced discharge	12V source in series	acc. UN38.3	discharging a discharged cell at $1I_t$ for 90 min.	discharging a discharged cell at $1I_t$ for 30 min. Until <0,25X V_{nom}	discharging a discharged cell at $1I_t$ for 90 min. The current is reduced depending on the number of available protections	discharging a discharged cell by the number of charged cells in the application in series and an 80mOhm resistor until V_{tot} <0,2V	acc. IEC62660-2	(module)
Imbalanced Charge								
Overcharge voltage control check					(battery)			
Overcharge current control check					(battery)			
Over-discharge current control check								
Environmental								
Altitude simulation	11,6 kPa, >6h	acc. UN38.3				close to UN38.3	acc. UN38.3	
Humidity								
Dewing								
Immersion							(battery)	
Salt spray / salt water immersion								2h in sea water
Rain test								
Electromagnetic susceptibility								

3.2. Selection of abuse tests for the Spicy project

Performing the complete UN38.3 is not necessary under condition that the cells will not be transported. Selecting some severe tests and test conditions from the 41 that are given in Table 7 seems most appropriate.

The mechanical tests may be restricted to vibration and crush test. For the first the conditions of IEC 62660-2 seems to be more severe due to the longer frequency band and the longer period. However the forces seem smaller.

The shock, drop, impact and penetration test are probably less necessary as long as the focus is on material development. Severe test conditions for the materials and cells will stem from the vibration and crush test. For the latter, the conditions in UN 38.3 seem most stringent.

In the temperature category the thermal stability test is most important. This test is almost a standard test for material developers. In this way also other tests are covered one way or the other, especially the high temperature endurance test.

In the electrical category the external short circuit test seems most vital as long as a low external resistance is used. Therefore, IEC 62660-2 is the best. The overcharge and forced discharge tests are more critical for battery developers than for material developers. Mitigation actions can e.g. come from the ‘black magic’ that is added to battery cells to obtain perfect behaviour. This is of lesser importance in the Spicy project.

From the environmental category, no tests are withheld in this proposition.

An overview of the proposition is given in Table 8. The selected tests and conditions are highlighted in green.

A discussion should be held to finalise the selection. Once this is decided, the exact test conditions can be sent around.

Table 8: Proposed tests and test conditions for the Spicy project.

Test topic \ Standard	UN38.3	IEC/EN 62281	IEC/EN 62660-2	IEC 62660-03 NWP	IEC 62619	UL 1642	Ellicert Battéries	(DOE) SAND2005-3123
Mechanical								
Vibration	7-200Hz, 12h, 1 to 8g_n	acc. UN38.3	10-2000Hz, 24h, 27,8 m/s^2			10-55Hz, 0.8mm, 95 min.	acc. UN38.3	
Mechanical Shock	150 g_n half sine of 6ms, 18x(cell)	acc. UN38.3	500m/s^2 half sine of 6ms, 30x(cell)	acc. Part2		shock from 75 to 150g_n, 3X	acc. IEC62660-2	(module)
Drop		(package box)			drop of 100cm		(battery)	(pack)
Cell impact	a bar on the cell, falling weight of 9kg, 60cm	acc. UN38.3			close to UN38.3	close to UN38.3		
Crush	crushing surfaces with 1,5cm/s until 13kN, 50% deformation or 100 mV voltage drop	acc. UN38.3	crushing bar or sphere, until 1000X cell weight, 15% deformation or voltage drop of 1/3 of V_{init}	acc. Part2, speed <6mm/min.		crushing surfaces with 1,5cm/s until 13kN	acc. IEC62660-2	(module)
Penetration							acc. SAE J2464	3mm steel rod with 8cm/s
Thermal								
Temperature cycling	-40 to 72°C, 10X	acc. UN38.3	-40 or $T_{min\ from\ manufacturer}$ to 85°C or $T_{max\ from\ manufacturer}$, 30X, wit or without electrical operation	acc. Part2		close to UN38.3	acc. UN38.3	-40 to 80°C cycling, 5X
High temperature endurance			130°C, 30 min.	acc. Part 2, 6h observation	85°C, 3h	≥130°C, ≥10 min., depending on cell's temperature specification	acc. SAE J2464	storing in 40, 60 and 80°C until 20% capacity decrease
Fire exposure						cell in flame until explosion or burn-out	(battery)	(module)
Thermal stability (ARC)								30 to 200°C above operational temp. until self-heating
Electrical								
External short circuit	<0,1 Ohm @55°C, >1h	acc. UN38.3	<5mOhm, 10 min.	acc. Part2	30 mOhm, 6h	80mOhm until 0,2V	acc. IEC62660-2	(module)
Internal short circuit				several methods, preferably an inserted nickel particle	insertion of nickel particle			
Overcharge	(battery)	(battery)	1$I_{t\,(BEV)}$ or 5 $I_{t\,(HEV)}$ until 200% SOC equivalent or 2X Vmax	1$I_{t\,(BEV)}$ or 5 $I_{t\,(HEV)}$ until 1,2 X V_{max} or 130% SOC equivalent	charge until max. voltage of charger that lost control, except if double protection is used.	3X $I_{max.\ charge\ by\ manufacturer}$, for 7h or reaching end of charge condition by manufacturer	acc. IEC62660-2	(module)
Forced discharge	12V source in series	acc. UN38.3	discharging a discharged cell at 1I_t for 90 min.	discharging a discharged cell at 1I_t for 30 min. Until <0,25X V_{nom}	discharging a discharged cell at 1I_t for 90 min. The current is reduced depending on the number of available protections	discharging a discharged cell by the number of charged cells in the application in series and an 80mOhm resistor until V_{tot} <0,2V	acc. IEC62660-2	(module)
Environmental								
Altitude simulation	11,6 kPa, >6h	acc. UN38.3				close to UN38.3	acc. UN38.3	
Salt spray / salt water immersion								2h in sea water

Annex Questionnaire sent to the Spicy partners

Background

Role of ageing tests in the project

The core of the Spicy project is well described by its title: ‘silicon and polyanionic chemistries and architectures of Li-ion cell for high energy battery’. In the project 3 cell generations will be developed, housed in 4 types of cell packaging and 2 cell sizes. Ageing tests (WP6) have a central role in the development of the new materials. Also modelling (WP7) plays a key role in the new battery cell generations. The modelling in its turn gets input from ageing tests (amongst others).

In the Ambition section of our project it has been phrased as follows:

‘We will provide test support to define standard ageing protocol for modelling study. SPICY will develop protocol of ageing on Li-ion cells made from reproducible processes allowing to fix parameter of electrolyte and material composition and see only the impact of cell architecture. Ideal cell dimensioning will be obtained from SPICY studies with a deep investigation of degradation issues.’

A test plan to age cells has to be developed (WP 6.3) limited by two issues:

- the available amount of cells, subdivided in materials, geometries and cell size, and to be shared over several test types: abuse testing, thermal and electrochemical characterisation, and ageing tests;
- the available test equipment like climate chambers, EIS devices and battery testers.

A full understanding of ageing phenomena is difficult since there are by far not enough cells available but also not enough testing equipment. To develop a test plan for battery ageing (WP 6.2) a balance has to be sought in the needed phenomena and the amount of cells. For specific phenomena, the cell architecture is of less importance, like calendar ageing. This makes it possible to reduce the number of cells without compromise.

This questionnaire has, as an objective, to know the ageing phenomena that are most needed by material developers and by battery modellers in order to be able to use as few as cells as possible and/or to distribute them as clever as possible over the different types of ageing tests.

Abstracts from the project text

The texts below give the official text abstracts on battery ageing and its applications. If you are in a hurry you can skip this section. It is the official wording of what has been written above.

WP 6

Objective 6: To develop test procedure to improve knowledge on ageing mechanism in order to provide input on cell design and materials properties

The tests will be designed according the assumed physic chemical ageing phenomena, as electrolyte decomposition, mechanical work, SEI formation etc.

WP 6.2

A design of experiment (D6.2) will be set up to plan the ageing test. This design of experiment is based on the capabilities, experience and available test infrastructure of the partners. Data required for models related to ageing and cycle life prediction will be specified and gathered. A test report template is defined (D6.2). There is an interaction with Task 7.4 and the test will be done in accordance the required ageing modelling parameterisation.

WP 6.3

At T0+ 6, 90 cells shared in 3 groups of cells architectures (cylindrical, prismatic winded, and prismatic stacked) will be provided to WP6 for performances, ageing test and safety test. At T0+18, 40 cells of GEN1 will be provided at T0+24 40 cells of GEN 2 and at T0+30 GEN3.

WP 6.4

Objectives are to give recommendation about cell geometry for future application in module and pack and see the impact of thermodynamic behaviour on the ageing. Moreover, based on electrochemical and thermal properties of material, dimension and design of the Li-ion cell will be done. The modelling effort will focus on the determination of electrochemical behaviour during charging and discharging. The amount of heat dissipated will be determined and parameter studies will enable virtual exploration of alternative designs. The task has a strong interaction with WP 7(modelling) and the data will be exchanged between both Tasks to verify the results and to get parameters for the simulation.

WP 7.4

Different ageing mechanism will be taken into account to describe the ageing of the different generation of cells within Spicy. In a first subtask we will identify the relevance of the known mechanism on the different generation of cells. Therefore the following mechanism will be analysed:

- Electrolyte reduction at the anode
- SEI formation at the anode
- Mechanical work by volume change (anode) and the resulting change in microstructure of the electrode
- Electrolyte oxidation at the cathode
- Interaction effects between both electrodes, for example dissolution of metallic components of the anode and deposition of these components in the anode/ anodic SEI
- Further effects

These mechanisms result on the one hand side in a reduction of capacity, as for example Li is consumed, but on the other side these mechanism influence the current path through the cell what requires different type of coupled models to describe these effects on a fundamental level. As the fundamental description of the total cell ageing is extremely complex and as there are not all ageing effects known today, within this task different levels of ageing effects will be investigated and described by models:

a. Empirical/semi empirical model. This model will be based on measurements form WP 6 and will not include a separate description of the several ageing effects.

b. Fundamental sub-models on different ageing mechanism, as electrolyte decomposition, SEI formation and mechanical work. For each ageing mechanism the chain of effects will be described and the required coupling will be analysed.

Both type of ageing models will be part of the electrode models and the basic 3D model as under development in tasks 7.2, 7.3 and. 7.4.

Approach

We, VITO unit Energy Technology, are asking to battery modellers and material developers what they need to know on ageing and what they suppose as being key ageing phenomena. This will be used to derive an ageing test plan for the available battery chemistries, cell sizes, cell packaging and cell generations.

As we have constraints of time, number of cells and available test equipment, here are some questions that would help the experimenters to design optimal tests procedures. It’s a non-exhaustive list of questions, you’re invited to add comments.

We ask you to fill in this questionnaire before Wednesday 8th July 2015.

Question list

Mechanism

1. What ageing mechanisms do you estimate to be of importance and which are probably dominant? The dominance can be related to the material and its operating conditions, but also be related to the specific model used by the modeller.

Models (to be skipped by material developers)

2. What kind of battery modelling will you do?

3. How (where) does ageing be reflected in the model?

Parameters (to be skipped by material developers)

4. What parameter input is needed for the model?

5. What parameters are specifically needed for the ageing effects?

Measurements

6. What measurement data (during calendar and cycle-life tests) is needed specifically to derive parameters for ageing phenomena?

7. Are you asking for post-mortem analysis and what parameters can you learn of it?

8. Are cycle-life tests needed or can calendar tests be sufficient? (The latter test method is less resource dependent, so easier to perform.)

9. Are the cell size and/or packaging of influence?

Test conditions

We consider, in this document, the following definitions:

SoC, state of charge: the capacity is based on a usual discharge rate *e.g.* 1C, at 25°C.

SoH, state of health: here it only refers to the battery capacity decrease.

The following conditions are considered as ‘usual test conditions’:

- C-rates: 1, 2 and 3C for charge and 1,2,3,…6C for discharge.
- Temperatures: 5°C, 25°C and 45°C for cycling and calendar tests.
- SoC window for cycling: 80% or/and 100% SoC (*e.g.* cycling from 20% to 100% SoC or from 0% to 100% SoC)
- SoC(s) for calendar ageing (storage): from 50% SoC to 100% SoC
- The end of life limit (EoL) is commonly (for automotive application) set to 80% of the initial capacity.

Battery technology	LFP/C		LFP/C_{opt}		$LFMP/C_{opt}$		LFMP/Si	
Questions	Yes/no	Comments	Yes/no	Comments	Yes/no	Comments	Yes/no	Comments
Are sub-zero temperatures interesting to test?		If yes, which temperatures?		If yes, which temperatures?		If yes, which temperatures?		If yes, which temperatures?
Are temperatures above 45°C interesting to test?		If yes, which temperatures?		If yes, which temperatures?		If yes, which temperatures?		If yes, which temperatures?
Are low C-rates (below 1C) interesting to test?		If yes, which one(s)?		If yes, which one(s)?		If yes, which one(s)?		If yes, which one(s)?
Are the SoC (State of Charge) window limits interesting to vary?		If yes, which one(s)?		If yes, which one(s)?		If yes, which one(s)?		If yes, which one(s)?
Are there specific SoH (State of Health) level(s) that need to be investigated in depth?		If yes, which one(s)?		If yes, which one(s)?		If yes, which one(s)?		If yes, which one(s)?
Is calendar ageing at low SoC (below 50% SoC) interesting to test?		If yes, which one(s)?		If yes, which one(s)?		If yes, which one(s)?		If yes, which one(s)?
Is calendar ageing at high temperature (above 45°C) interesting to test?		If yes, which temperatures?		If yes, which temperatures?		If yes, which temperatures?		If yes, which temperatures?
What battery technology is worth autopsy?								
At which test condition an autopsy will deliver relevant information?								
At which SoH an autopsy will deliver relevant information?								

Battery technology	LFP/C	LFP/C_{opt}	LFMP/C_{opt}	LFMP/Si
At which SoC an autopsy will deliver relevant information?				

Extra remarks:

…

Annex Analysis of EV logging data

VITO has a database with logging data of electric vehicles. A summary is given in Table 9. This is useful to establish the ranges in the characterisation tests and ageing tests. Only data is used when the vehicle was driving.

Table 9: Summary of EV logging data.

Vehicle	EV type	Nom. capacity (Ah)	# Cells (-)	Nom. battery volt. (V)	Car number	C-rate (-) min. (=discharge)	max. (=charge)	mean. (discharge)			mean. (charge)			Battery voltage (V) min.	max.	mean			Speed (km/h) mean			max
Ampera	EREV		222	360	*1*	-6,8	3,4	-0,8	±	0,6	0,7	±	0,5	306	398	370	±	12	54	±	25	140
					2	-7,5	3,8	-1,0	±	1,0	0,8	±	0,7	284	397	351	±	11	84	±	45	166
					3	-7,8	3,9	-0,9	±	1,0	0,9	±	0,7	273	397	348	±	8	71	±	42	165
					4	-7,7	3,7	-0,7	±	0,8	0,6	±	0,6	280	399	350	±	9	75	±	39	162
					5	-7,6	3,8	-1,1	±	1,1	0,8	±	0,7	298	398	361	±	15	51	±	32	163
					average	***-7,5***	***3,7***	***-0,9***	***±***	***0,9***	***0,8***	***±***	***0,6***	***288***	***398***	***356***	***±***	***11***	***67***	***±***	***37***	***159***
Leaf	EV		192	365	*1*	-4,3	1,9	-0,6	±	0,4	0,3	±	0,2	259	395	372	±	12	62	±	31	148
					2	-4,0	1,7	-0,8	±	0,6	0,4	±	0,4	287	394	373	±	12	67	±	34	149
					3	-4,0	1,7	-0,7	±	0,5	0,3	±	0,3	343	394	379	±	7	66	±	31	136
					4	-4,0	1,8	-0,5	±	0,4	0,2	±	0,2	328	394	376	±	8	49	±	25	132
					average	***-4,1***	***1,8***	***-0,6***	***±***	***0,5***	***0,3***	***±***	***0,3***	***304***	***394***	***375***	***±***	***10***	***61***	***±***	***30***	***141***
Fluence	EV		192	398	*1*	-3,4	1,0	-0,3	±	0,3	0,4	±	0,3	174	395	382	±	8	42	±	20	119

It appears that there is not much difference between the vehicles per type. Between the types there is of course dissimilarity. The Opel Ampera, an EREV, has C-rates that double with respect to the Nissan Leaf and Renault Influence, full EVs, notwithstanding that the battery capacity is not half the one of the Leaf and of the Influence. The highest factor between the maximum discharge rate and the average discharge rate is found for the Fluence: 11. For the Ampera this is 9 and for the Leaf 6. Anyway, there is a large difference between the average value and the maximum value. The factor between the maximum charge rate and the average charge rate shows a different trend. Here the Fluence has the lowest ratio with 2. The Leaf has a factor of 6 and the Ampera a factor 5.

It appears that the batteries of all three car types have the same maximum voltage: just not 400 V. The Nissan Leaf shows a large spread in the minimum voltage, see Figure 1. A counterintuitive finding is that the average voltage is lower for the EREV than for the EV types. For the Leaf and Influence the average voltage is quite close to the maximum voltage, whereas for the Ampera this is roughly in the middle of the maximum and minimum value.

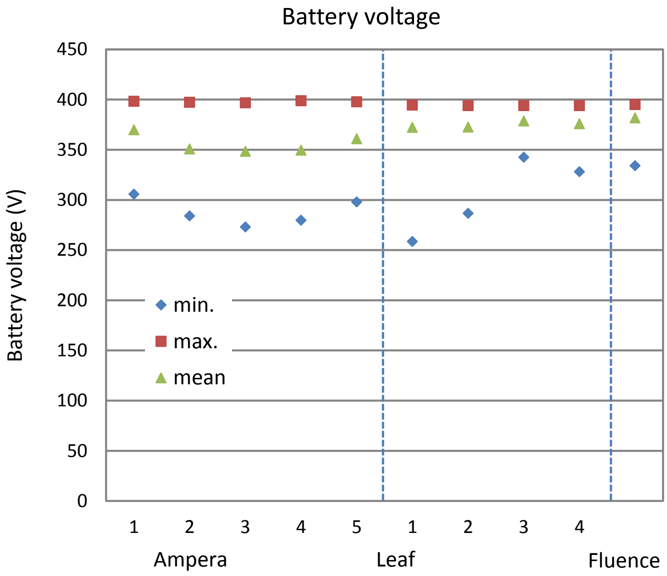


Figure 1: Summary data for the battery voltages