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Enhanced test methods to characterise automotive battery cells

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ABSTRACT

This article evaluates the methods to characterise the behaviour of lithium ion cells of several chemistries and a nickel metal hydride cell for automotive applications like (plug-in) hybrid vehicles and battery electric vehicles. Although existing characterisation test methods are used, it was also indicated to combine test methods in order to speed up the test time and to create an improved comparability of the test results. Also, the existing capacity tests ignore that cells can be charged at several current rates. However, this is of interest for, e.g. fast charging and regenerative braking. Tests for high power and high energy application have been integrated in the enhanced method. The article explains the rationale to ameliorate the test methods. The test plan should make it possible to make an initial division in a group of cells purchased from several suppliers.

1. Introduction

In Belgium a consortium of twelve companies and research faculties tied together to find the optimal battery cells on the market in order to develop a complete battery system [1]. Even though the interest is in automotive applications, this ranges from hybrid electric cars with a battery of 3 kW h up to battery electric cars with a battery of 25 kW h. This means that both high power and high energy applications are foreseen. There are batteries on the market that have been designed for either of these two applications. Also, the test results should be able to distinguish the good battery cells for either application.

In order to find the optimal cells from which battery packages can be made, two types of test regimes have been foreseen:

– characterisation tests;
– lifetime tests.

Although the lifetime tests are most important to know how cells withstand their ultimate task, characterisation tests are needed to find the better cells, to separate them in high power and high energy application and to reveal the individual key strength. Other test methods like reliability tests and abuse tolerance tests, like proposed in [2], are not foreseen within this phase.

This article starts with a review of existing characterisation methods and explains which battery properties can be derived with the individual test schemes. However, in order to speed up the tests and to obtain results that enable good comparison of the cells, the need exists to enhance the existing test methods. This necessity will clearly be explained. Afterwards an enhanced test methodology is set up. In a separate article the test method will be used to evaluate a large group of cells. Partial test results can be found in [3–5].

2. Intended applications and basic cell properties

To evaluate existing characterisation tests, it is necessary to have insight in the demands imposed by the intended applications and in the basic properties of the cells to be tested according to their data sheets. This is necessary as the proposed tests should fit with the anticipated applications, but also with the cells that will be tested.

The consortium has agreed on 4 applications: hybrid electric car (HEV-PC), hybrid electric bus (HEV-B), plug-in hybrid electric car (PHEV-PC) and battery electric car (BEV-PC). A short outline of the requirements is given in Table 1. The basic properties are total battery system voltage, the energy to be stored and the (dis)charge power. From these figures an impression can be obtained of the battery size expressed in ampere hours (Ah) and in C-rates for

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Table 1
Battery requirements for our 4 automotive applications.

Vehicle type	HEV-PC	HEV-B	PHEV-PC	BEV-PC	
Voltage	300	600	300	300	V
Stored energy	3	18	10	25	kW h
Max. charging power	24	48	24	24	kW
Max. discharging power	45	120	60	60	kW
Battery size	10	30	33	83	Ah
Max. charging current	80	80	80	80	A
Max. discharging current	150	200	200	200	A
C-rate charging	8	2.7	2.4	1.0	C
C-rate discharging	15	6.7	6.0	2.4	C

charging respectively discharging. Normally, the C-rate is derived by the actual current in ampere and the actual cell or battery capacity in Ah. In the table the needed current is simply divided by the needed battery size. The selected applications need a charge C-rate between 1 and 8 as well as a discharge C-rate between 2 and 15.

The objective is to test both lithium-ion cells of several chemistries and nickel metal hydride cells given that the latter are the reference and will play in the near future an important role for automotive applications. 13 different cells have been obtained that are tabulated in Table 2. The table provides a short list of properties of the cells that are important to consider for the appropriateness of the characterisation tests and the appropriateness for the applications. The cells have been arranged by chemistry and cell size. Nine of the 13 cells are lithium-ion iron phosphate cells (LFP). Further, there is one lithium nickel cobalt aluminium oxide cell (NCA), two lithium-ion nickel manganese cobalt oxide cells (NMC) and one nickel metal hydride cell (NiMH).

The cells show a wide variety in shapes and connection methods. These characteristics are important for the mechanical integration of the cells in a battery package. They can also have an influence on the weight density and the temperature performance. Although most of the cylindrical cells have a modest capacity (around 3 Ah) in comparison with the intended application, they constitute the largest actual market share.

Cell manufacturers provide often the (dis)charge rates expressed in ampere. Since all cell capacities are unequal, it is better to express the (dis)charge rates as a C-rate. This is only correctly possible if the 1 h discharge rate is given. However, this is not always the case since some manufacturers give the 2 h and 5 h discharge capacity, what is not necessarily the same value. In the table the C-rate is obtained by simply dividing the announced current with the capacity according to the manufacturer. The (dis)charge rates in Table 2 have been split up in four categories: recommended rate, maximum rate, recommended pulse rate and maximum pulse rate. Since a pulse cannot be persisted for an arbitrary duration, the duration should be given for the pulse rates. However, the manufacturers do not always provide these data. The table makes also clear that more data is provided on discharging than on charging cells.

The continuous discharge rate is between 5 C (1 cell) and 20 C (2 cells) and even 30 C (1 cell) for lithium ion cells and 2 C for the NiMH cell. 8 cells can withstand at least 20 C pulses, with a declared duration varying from 1 s up to continuous. Take into mind that a continuous 20 C discharge means that a cell is empty in 3 min! The maximum allowable temperature for discharge is in between 45 and 75 °C.

The continuous charge rate is between 0.5 C (1 Li-ion cell and the NiMH cell) and 4 C (2 cells). Only two manufacturers give information on charging with a pulse, of which one is not offering the duration. This general lack of pulse charge information is striking, as it is an important parameter for regenerative braking in vehicle applications. The maximum allowable temperature charging cells is almost always lower than for discharging and is in between 45 and 60 °C.

Some conclusions can be drawn confronting Table 1 with 2 for the most demanding purpose of hybrid electric car (HEV-PC), the second most demanding one i.e. a hybrid electric bus (HEV-B) and the less demanding of the battery electric car (BEV-PC). It can be deduced that the 15 C discharge demand for HEV-PC can be fulfilled by 3 cells under continuous conditions and by 6 cells under pulse condition. However, the 8 C charging for the HEV-PC is not possible according to the data sheets. Even the 3 C charging for the HEV-B is not generally possible, i.e. for 5 cells. The discharge rate of 2 C for the BEV-PC is possible for all cells, whereas the charge rate of 1 C is possible for 8 out of 13 cells.

3. Overview of characterisation tests

Although some cell test methods are described in the scientific literature [6–12], as a rule one uses individual test schemes to evaluate the performance of batteries. Unfortunately, these are not based on the international standards that are under development. In this article the main international battery test standards that exist are applied, i.e. [2,13–17]:

- draft IEC 62660-1 (performance testing for lithium-ion cells);
- draft ISO/DIS 12405-1 (lithium batteries for vehicles, high power applications);
- draft ISO/DIS 12405-2 (lithium batteries for vehicles, high energy application);
- IEC 61982-4 (battery test for BEV);
- FreedomCAR battery test manual (battery tests for HEV);
- DOE Battery test manual for plug-in hybrid electric vehicles (tests for PHEV).

The next paragraphs will describe the scope of each of these standards, their test contents regarding cell characterisation, the difference and overlap and how they are combined into one set of characterisation tests.

3.1. Draft IEC 62660-1

The IEC draft is specifically under development for cells, both for HEV and BEV application. It comprises a characterisation and a life cycle test. To characterise cells it contains the following methods:

A capacity test: a full discharge at 0.33 C for BEV application and 1 C for HEV application, at 0, 25 and 45 °C.

A power test: a pulse train of 5 identical discharge and charge pulses of 10 s each, performed at 20, 50 and 80% SOC. The pulse train is different for BEV and HEV application. For BEV it is 0.33 C; 1 C; 2 C; 5 C and I_{max}. For HEV 2 C is omitted and 10 C is added. Between the pulses there is a 10 min rest period. Power and power densities can be calculated afterwards.

Table 2
Cell specifications according to manufacturers.

ID	Cell					Charging					Discharging					
	Cathode	Shape	Connection	Capacity (Ah)	C-rate (C)	Recomm. cont. (C)	Max. (C)	Max. pulse (C)	Period (s)	Max. temp (°C).	Recomm. cont. (C)	Max. cont. (C)	Recomm. pulse (C)	Max. pulse (C)	Pulse period (s)	Max. temp. (°C)
A	LNMCO	Pouch	Flap	70	0.5	0.5	2			45	0.1	5	1	8	10	55
B	LNMCO	Pouch	Flap	12	0.5	0.5	3			45	0.5	18	9	23	10	55
C	NCA	Cylinder	Screw	27	0.2	1	4	6	15	40	2	10		28	2	60
D	LFP	Prismatic	Screw	45	0.5	0.5				60		10				70
E	LFP	Pouch	Flap	40	0.2	0.5	2			45	1	10				60
F	LFP	Prismatic	Screw	30	1	0.5				60		10				70
G	LFP	Pouch	Flap	14		0.5				40		10		20	10	50
H	LFP	Pouch	Flap	10	1		3	6	?	45		20		40	?	65
I	LFP	Cylinder	Screw	10	0.2		3			45		8		20	1	75
J	LFP	Cylinder	Side	3.5	0.2	1	2			45		10				45
K	LFP	Cylinder	Side	2.5	0.2	0.2	0.5			45	6	6		20	?	60
L	LFP	Cylinder	Side	2.3		1	4			60	30			52	10	60
M	NiMH	Prismatic	Screw	30	0.2	0.5				45		2				50

A storage test: a cell is stored at 50% SOC and 45 °C for 28 days. The self discharge is measured afterwards.

3.2. *Draft ISO/DIS 12405-1*

Although the scope of the ISO document is on battery packs and systems, its test methods could be used for cells as well. It comprises characterisation and life cycle tests, together called 'general tests'. It also has reliability tests and abuse tests. Fig. 1 shows the test set-up. Concerning the characterisation tests it contains:

- *Preconditioning test*: Performed on battery packs and on systems to stabilise their performance. 5 cycles are executed consisting of a 2 C discharge and a charge according to the manufacturer. The capacity value should not change more than 3% between two consecutive discharges to consider the battery as preconditioned.
- *Standard cycle*: A 1 C discharge and a charge according to manufacturer.
- *Energy and capacity test at room temperature (RT)*: It is applied on battery packs and systems. It comprises capacity tests at 1 C, 10 C and maximum current. The charge rate is according to the supplier.
- *Energy and capacity test at other temperatures*: The same capacity tests but at 40 °C, 0 °C and −18 °C. After each capacity test a discharge–charge cycle at room temperature is performed. In total 28 cycles are performed.
- *Power and internal resistance test*: It is applied on battery packs and systems. It demonstrates the discharge pulse power capabilities at maximum discharge rate (up to 18 s) and the regenerative pulse power capabilities at 0.75 times the maximum discharge rate (up to 10 s). Between both pulses a 40 s wait period exists. The pulse train is executed at 5 SOC levels: 80, 65, 50, 35 and 20%. The test is performed at RT, 40 °C, 0, −10 and −18 °C. From the voltage change during the pulses resistance and power values can be calculated.
- *State of charge (SOC) loss tests*: These tests are for battery systems only and measure the capacity loss over a long period without use.
- *Cranking power at low temperature*: The test happens at −18 °C and preferably also at −30 °C. The test starts at 20% SOC or the lowest one allowed by manufacturer. A discharge during 5 s is applied with constant voltage discharging at minimum allowed voltage, however with a restriction to maximum allowable power. The discharge is repeated 3 times with a 10 s pause in between. The aim is to generate a data basis for time depending power output at low temperatures.
- *Cranking power at high temperature*: The test demonstrates the power capability at 50 °C or the maximum temperature allowed by manufacturer. The test is the same as the previous one.
- *Energy efficiency test*: The test is foreseen for battery systems only. The energy efficiency can be calculated of a discharge pulse of 20 C (or the maximum allowed one) for 12 s and a charge pulse of 15 C (or 0.75 times maximum allowed discharge pulse) during 16 s. The test is executed at 3 SOC levels, i.e. 65, 50 and 35%. 3 Temperatures are envisaged: RT, 40 °C and 0 °C.

3.3. *Draft ISO/DIS 12405-2*

This standard is meant for high energy applications instead of high power application as for the previous one. This draft standard entails many of the tests of the previous one, but three are omitted: the cranking power at both low and high temperature as well as the energy efficiency test. One test is added: the energy effi-

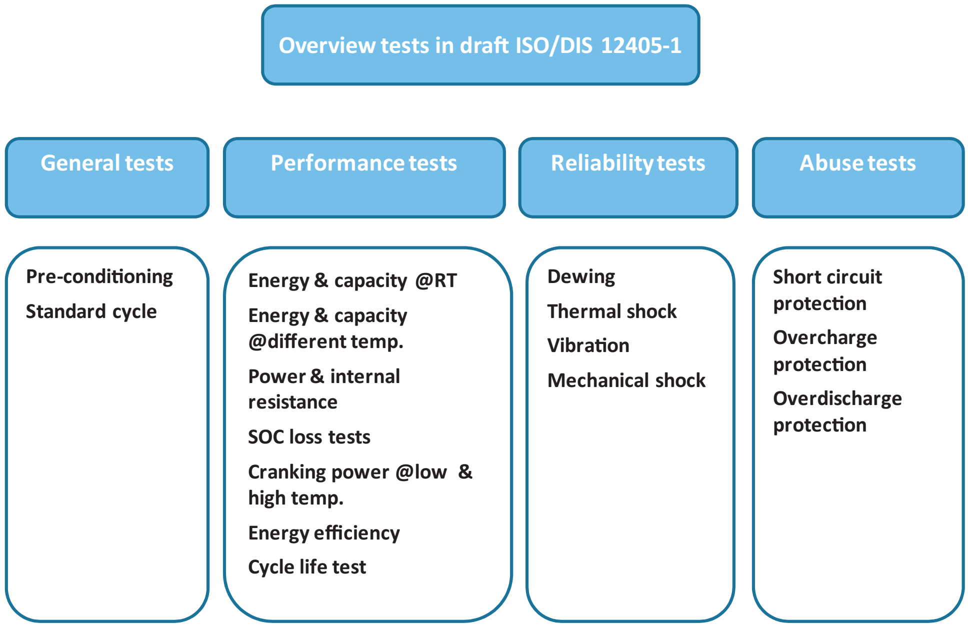

Fig. 1. the characterisation plan according to draft ISO/DIS 12405-1.

ciency test at fast charging. Although the tests resemble each other, many parameters, such as current, SOC and temperature have been changed. The characterisation methods consist of:

- *Preconditioning test*: Identical as previous standard.
- *Standard cycle*: Identical as previous standard.
- *Energy and capacity test at RT*: The C-rates have been reduced to: 0.33 C; 1 C; 2 C and max. current. The charge rate is according to the supplier. This means that 0.33 C is added and 10 C omitted.
- *Energy and capacity test at other temperatures*: The same capacity tests but at 40 °C, 0 °C and −10 °C and −25 °C. This means that −18 °C is replaced by −10 and −25 °C.
- *Power and internal resistance test*: The maximum discharge and charge rate have been maintained from the corresponding test in the previous standard. However, the discharge pulse is lengthened from 18 s to 120 s and the charge pulse from 10 s to 20 s. Also the SOC levels have been changed a bit: 90, 70, 50, 35 and 20%. Regarding the temperatures, −25 °C has been added to the test regime.
- *SOC loss tests*: The same as in the previous standard.
- *Energy efficiency at fast charging*: It is applied on battery systems only. It derives the roundtrip efficiency for fast charging. It consists of a standard discharge combined with respectively 1 C, 2 C and I_{max} charge.

3.4. IEC 61982-4

This standard comprises a characterisation and a life cycle test. The characterisation test is called the dynamic discharge performance test. It derives a battery capacity which is closely related to the available capacity in an electric vehicle. The currents are referred to the 3 h discharge rate, C3. It consists of a 60 s cycle with amplitudes of 5.2 C3 and 1.3 C3 discharge and 2.6 C3 charge. The profile is repeated until the minimum allowed voltage as declared by manufacturer is attained.

3.5. FreedomCAR battery test manual

The tests in the FreedomCAR manual have been constructed to verify that batteries are able to fulfil the hybrid power assistance task. Often the emphasis is on delivering an amount of power expressed in kW at certain states of charge. It has not been developed to compare cells with each other. The tests can be used for subsystems down to cells by introducing scaling factors, called battery size factor, that are based on the dimensioning of the battery system. The manual comprises characterisation and life cycle tests. In addition some system and module verification tests are included. The tests can also be used to fit a powerful battery model. The characterisation tests contain:

- *Static capacity test*: A full discharge at 1 C. No charge rate is given.
- *Hybrid pulse power characterisation test (HPPC)*: It has a profile consisting of a discharge pulse at I_{max} for 10 s, waiting for 40 s and a charge pulse at 0.75 I_{max} during 10 s. The pulses are performed at 10% DOD up to 90% DOD with a 10% interval, resulting in 9 pulse trains. Between the pulse trains there is a 1 h rest. There is also a low and a high current HPPC test that respectively applies 0.25 I_{max} and 0.75 I_{max}.
- *Self discharge test*: The time needed that battery discharges 5% beginning at 70% SOC has to be measured.
- *Cold cranking*: A pulse train of 2 s pulses of either 5 or 7 kW at −30 °C. The maximum DOD that still delivers the power has to be found.
- *Thermal performance test*: The tests stated above can be performed at temperatures between −30 and +52 °C. No specific temperature scheme is given.
- *Energy efficiency test*: It determines the round-trip efficiency by a charge-balanced pulse profile with a maximum 15 kW system discharge and a 12 kW system charge.

3.6. DOE battery test manual for plug-in hybrid electric vehicles

It is based on the FreedomCAR test manual. It is for full-size battery systems but can be used for packs and cells using a battery size factor. It contains characterisation and lifetime tests. Core element in the tests is the HPPC current. It represents the steady state current during the 10 kW constant power discharge test. If that current is unknown it may be replaced by 1 C. The characterisation tests are:

– Static capacity test: a capacity test through a full discharge at HPPC-current rate. No charge current is given.
– Hybrid pulse power characterisation test: like in the FreedomCAR test manual, however with pulses at 75% of the maximum pulse discharge current as defined by the manufacturer (this is 100% in the FreedomCAR manual).
– Self- discharge test: measurement of the remaining capacity after a certain time, recommended is 7 days.
– Cold cranking test: the determination of the 2 s power capability at −30 °C at maximum allowed depth of discharge with a 7 kW pulse. This is like in the FreedomCAR manual.
– Thermal performance test: a repetition of static capacity test at temperatures between −30 °C and +52 °C. No temperature scheme is given.
– Energy efficiency test: determination of the round-trip efficiency by a charge-balanced pulse profile of 90 s with max. 27 kW system discharge and 18 kW system charge. After 100 repetitions a possible change in SOC should be detected by means of change in OCV. The test resembles the one in FreedomCAR but with almost twice the power. The power should be adapted to find the exact efficiency in order that the SOC does not change. It can be scaled to module and cell level.

4. Discussion on characterisation tests

The test standards are all for lithium-ion batteries except IEC 61982-4 that can be used for all automotive batteries.

– From the review it can be concluded that the characterisation tests proposed in the standards are quite different. A couple of test methods are found in most of the standards:
– Capacity tests consisting of full discharges and recharges of a battery, also called energy and capacity test as well as efficiency test at fast charging.
– Pulse tests under the names power test, power and internal resistance test, energy efficiency test and hybrid pulse power characterisation test. It contains a pulse train consisting of a combination of a discharge an charge pulse, sometimes at several C-rates. The pulses can also be expressed in kW in the FreedomCAR manual and DOE Battery test manual.
– Cranking test at cold and possibly high temperature.
– Self discharge test, also under the names storage test and SOC loss test.

The tests are often repeated at several temperatures. Notwithstanding that the above four test categories can be discerned in the standards, they are always executed with dissimilar charge rates, rest periods and SOC levels. So, it is not possible to bring those tests easily together.

The ISO/DIS 12405-1 and 2 adds a preconditioning test to verify that the capacity of the cells are stable, since during the first cycles of a new cell its capacity can increase or the cell may quickly perform badly due to a production failure. The standard IEC 61982-4 contains one characterisation test and that one is not found in the other standards: a dynamic discharge performance test to derive the available capacity and other characteristics in a way that is close to the battery electric vehicle.

The completeness of both ISO/DIS 12405 methods is indicated. It consists of a precondition test, several capacity tests, a pulse test, a self discharge test and a cranking test. The pulse test is however confined to only one pulse strength, i.e. the maximum allowed pulse current. If the dynamic discharge test is added, a complete test scheme is obtained out of the standards.

The C-rates in the IEC 62660-1 are referring to the capacity as given by the manufacturer, called I_T. This is not (necessarily) the same as the classic 1 C value (the battery capacity of a full discharge during exactly 1 h). Although for many lithium-ion cells the capacity is hardly dependent on the C-rate, this is not for all manufacturers the case and it makes comparison more difficult. Moreover, tests derive that some manufacturers claim a capacity value that is not confirmed by the capacity tests. The capacity tests make it quite easily possible to obtain the exact 1 C value that thereafter can be used as reference.

4.1. Capacity test

The standards show a wide variety in C-rates for the capacity test from 0.33 C in IEC 62660-1 for BEV application up to maximum allowed current in both ISO/DIS 12405. The longest range is prescribed in ISO/DIS 12405-2 with a series of four C-rates. The charge is executed at the prescribed charge rate by the manufacturer. ISO/DIS 12405-2 contains an extra test, the energy efficiency test at fast charging, that uses two specific charge rates, i.e. 1 C and 2 C.

The very known Peukert constant is in neither of the standards derived. The discharge series of ISO/DIS 12405-2 makes its calculation however possible. Notwithstanding that the Peukert constant is close to 1 for most of the lithium batteries, it is still considered as an interesting aspect.

The emphasis on high discharge rates in ISO/DIS 12405-1 with series of 1 C, 10 C and I_{max} complements the low discharge rates series of ISO/DIS 12405-2 with series of 0.33 C; 1 C; 2 C and I_{max}. This covers all standards.

At one exception all the proposed capacity tests in the standards discharge at several rates but charge the cell only with the recommended charge rate by the manufacturer. This is unnecessary, as many cells are allowed to be charged at higher rates. It is interesting to include that property into the tests. Another distinguishing quality that can be found during charging a battery is the SOC of a battery when it attains the maximum allowable voltage. At that moment charging switches to constant voltage charging. Due to the reduced current, the charging time increases to obtain a 100% SOC. So, the higher the SOC before attaining the maximum voltage, the quicker a cell is charged.

By charging and discharging at the same rate, e.g. 5 C, the efficiency of the 5 C cycle is obtained. This will probably be lower than a combination of 5 C discharge and a charge as proposed by the manufacturer. If the charge rate is not allowed to be as high as the discharge rate, then using the highest allowed charge rate still leads to the efficiency of the nearest combination. If one would like to have insight only in the influence of the discharge rate on the efficiency, then a 1 C charge is preferred instead of a manufacturer proposed charge to ensure comparability of the test results between different brands.

4.2. Pulse test

The pulse trains from the pulse tests as found in the standards are visualised in Fig. 2.

The pulse tests described in IEC 62660 are the most complete ones with a pulse train of 5 different pulse rates, making a distinction between HEV and BEV applications. The pulses in the other test prescriptions are at the maximum allowed current (expressed in ampere) or 0.75 times this value. However, this value is not the same for all cells. On the contrary, as is indicated in Table 2. This makes comparison of the results difficult.

The pulse profile is executed at certain SOC levels, varying from 3 levels in IEC 62660, 5 levels in both ISO/DIS 12405 and 9 levels in the FreedomCAR manual. Together, the standards cover a range of at least 80–20% SOC and maximally 90–10% SOC. To go from one SOC level to the next, in the IEC 62660 the cell is fully charged after a

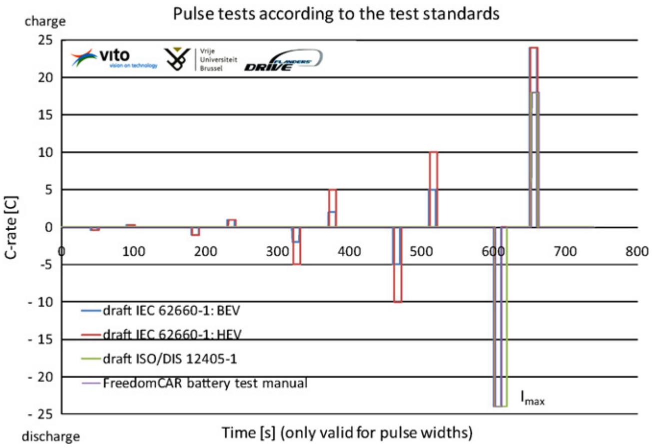

Fig. 2. Pulse trains as found in the pulse tests in the standards. The time between pulses is not visualised according to the standards.

discharge and charge pulse combination and then discharged to the next SOC level. This is a precise method, but very time consuming. Its pulse train of 5 discharge and charge pulses takes 112 min. If the time between pulses is reduced to 40 s like in the ISO/DIS standards and the FreedomCAR manual, then the pulse train takes only 9 min. The latter standard prescribes that nevertheless care has to be taken that the cell temperature is less than 2 °C higher than the required temperature before starting a new pulse.

The pulse train prescribed in the IEC 62660 allows the best comparison of the cells. Also, in this way, insights can be gained in the pulse efficiency for small pulses up to high pulses. When both prescribed pulse trains for HEV and BEV are combined, given that only two pulse rates are different, it results into a series of 7 pulses.

It is important that the cell remains at roughly the same SOC level after each discharge and charge pulse combination, a so-called charge sustaining operation. Therefore, it is important that (unlike the HPPC test in the FreedomCAR manual) both pulses are identical. If the maximum allowed charge pulse is lower than the discharge pulse, the duration should be increased proportionately to maintain the charge balance.

A test has been set up to get insight in the consequences of the differences that are found in the standards. The test should point out that it is possible to perform the pulse trains at each prescribed SOC level without a full charge in between. It should also show the influence of the pause periods between the pulses on the cell performance and on the parameter fitting according to the FreedomCAR model [18]. If all pauses can be 40 s without having an influence on the performance then the test can enormously be accelerated. The test consists of a series of 2 C, 5 C, 10 C and 20 C discharge and charge pulses. The rest periods between charge and discharge pulse, respectively the rest period after the charge pulse are varied according to:

- 10 min and 10 min;
- 40 s and 10 min;
- 40 s and 40 s.

The pulse train is executed at 80, 50 and 20% SOC. The test is performed on NMC 12 Ah cells: cell B in Table 2. It has been performed with 5 cells and is repeated three times.

The overall capacity found by subtracting the total discharge and the total charge during the test cycle, appears to be very close to the 1 C capacity: 12.15 ± 0.03 Ah against 12.25 ± 0.01 Ah. This will also mean that the intended SOC levels have been well applied.

The influence of the pause period is shown in Table 3. It shows the results for the pulse efficiency and power as well as for the fitting parameters according to the FreedomCAR model. It appears that, for an individual cell, the pulse properties for a 40 s–40 s pause, are deviating from the results with longer rest periods. If all cells are taken into account, the differences almost fall within the measurement variation. To measure pulse properties a respective pause period of 40 s between the discharge and charge pulse and 10 min after the charge pulse is sufficient.

The data of the maximum discharge and charge pulse at each SOC level can be also used to fit the FreedomCAR model. This model is a lumped parameter battery model existing of two resistors, two capacitors and the open circuit voltage (see Fig. 3). The parameters follow from a fit to the test data, provided that the pulses are stored with an adequate number of data points. The fit should be repeated for each SOC and temperature. This results into a matrix of parameter values. For the parameter fitting, the result shows that the fitted values of R_p and τ (see Fig. 3 for the meaning) deviate for rest periods shorter than 10 min, although the results are still close to each other. Only one pulse rate at one SOC level is given in the table for conciseness. For the other pulse rates and SOC levels the trend appears to be the same.

4.3. Cranking test

ISO/DIS 12405-1, the FreedomCAR manual and the DOE Battery test manual entail cranking tests. The first one is prescribed at −18 °C with a preferred test at −30 °C. The latter temperature is prescribed in the FreedomCAR manual and DOE Battery test manual. The test method is quite different: a fixed crank pulse expressed in

Table 3
Influence of pause period between pulses on cell properties and parameter fitting.

	Pause period	Efficiency (%)	Pulse power (W)
Pulse properties for a 20 C pulse at 50% SOC			
One cell (3 repetitions)	10 min–10 min	75.0 ± 0.2	661 ± 2
	40 s–10 min	75.5 ± 0.2	665 ± 1
	40 s–40 s	77.1 ± 0.1	682 ± 1
Average of 5 cells	10 min–10 min	75.7 ± 0.9	665 ± 7
	40 s–10 min	76.2 ± 0.9	669 ± 7
	40 s–40 s	77.8 ± 0.8	687 ± 7

	Pause period	OCV (V)	R_O (mOhm)	OCV′ (μV C^{-1})	R_p (mOhm)	τ (s)
Fitting parameters for a 20 C pulse at 50% SOC						
One cell (3 repetitions)	10 min–10 min	3.6989 ± 0.0002	3.00 ± 0.03	13.0 ± 0.1	1.76 ± 0.02	21.3 ± 0.2
	40 s–10 min	3.7000 ± 0.0003	2.96 ± 0.02	14.0 ± 0.1	1.49 ± 0.01	18.0 ± 0.2
	40 s–40 s	3.7067 ± 0.0007	3.33 ± 0.02	18.0 ± 0.1	1.36 ± 0.00	16.70 ± 0.06
Average of 5 cells	10 min–10 min	3.6990 ± 0.0003	2.9 ± 0.1	13.0 ± 0.1	1.7 ± 0.1	20.3 ± 0.9
	40 s–10 min	3.7001 ± 0.0003	2.9 ± 0.1	14 ± 1	1.4 ± 0.1	16 ± 2
	40 s–40 s	3.7067 ± 0.0007	2.8 ± 0.3	16 ± 1	1.34 ± 0.03	15.8 ± 0.7

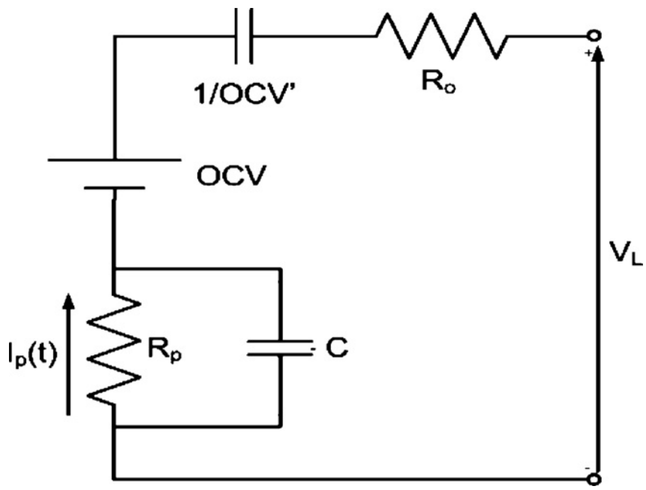

Fig. 3. FreedomCAR linearised lumped parameter battery model.

kW for the FreedomCAR test and DOE Battery test manual, against a constant voltage discharge in the ISO/DIS standard at one SOC level (20%). This may lead to high currents. It is quicker performed than searching for the lowest SOC level that is still able to deliver the prescribed power level as foreseen in the FreedomCAR test.

Cranking at high temperature is only foreseen in the FreedomCAR manual.

4.4. Self discharge test

Self discharge tests are all based on storing a cell or complete battery system without use for some period of time. The SOC level, the period and the temperature do differ for all tests.

5. Enhanced test methodology

Given the analysis of the characterisation test methods the following characterisation tests can be based on the standards:

- pre-conditioning in order to prepare the fresh cells and as a first quality control;
- capacity test at several discharge and charge rates;
- dynamic discharge test in order to obtain many cell properties like efficiency under dynamic conditions closer to reality than during capacity tests;
- an integrated pulse test consisting of the HPPC test, the energy efficiency test and the power and regenerative braking test.

This set-up is visualised in Fig. 4.

The tests are first performed at room temperature and a selection of the cells will be submitted to tests at other temperatures. Each test will be executed with 5 samples of each cell. This enables data on the repeatability of the tests and the variation between the species. In the next paragraphs, a detailed description of the individual tests is provided and suggested adaptations to the originals are described.

Since it is envisaged to start with tests at room temperature, the cranking tests have been omitted. The test standards foresee also a self discharge test for battery packs and systems. However, lithium-ion cells have themselves in general (without electronics attached) a low self discharge rate, this test is left out as well.

None of the test standards describe the slope of the pulses. In this way the slope depends on the quality of the cell test machine and can consequently vary, in practice between 1 ms and 1 s.

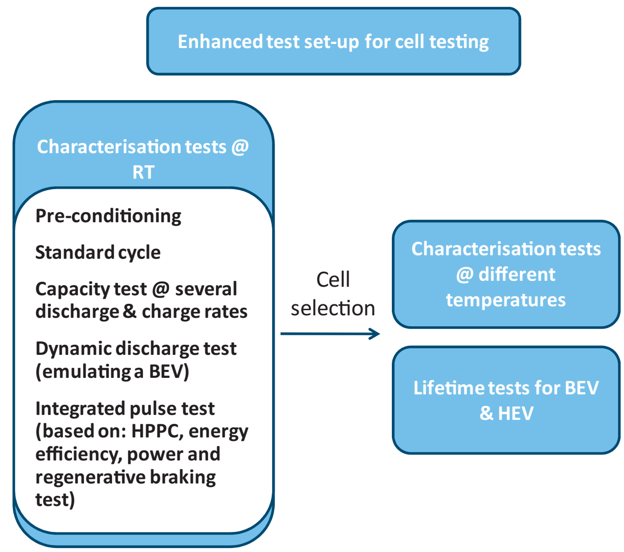

Fig. 4. Enhanced test set-up.

All the tests commence with a standard charge, i.e. the recommended charge by the manufacturer to be sure that the cells are fully charged.

5.1. Preconditioning test

The preconditioning is taken from the ISO/DIS 12405-1 and 2. It consists of a series of 5 times discharging and charging a cell. Discharging happens at a discharge rate of 2 C, or I_T in case as the 1 C capacity is not determined and charging with the recommended charge rate by the manufacturer. The difference in capacity between the cycles should be less than 3% to consider the cell as preconditioned, else the sample has to be replaced and the test repeated. A standard charge is added by the end consisting of a 1 C or 1 I_T discharge and the recommended charge to obtain a capacity reference that may show how the cells alter during the subsequent tests.

The duration is about 20 h.

5.2. Capacity test at room temperature

The capacity test is based on ISO/DIS 12405-1 and 2. The test is performed at 6 discharge rates and equivalent charge rates if allowed, i.e.: 0.33 I_T, 1 I_T, 2 I_T, 5 I_T, 10 I_T and max. allowed I_T. After each (dis)charge a rest period of 30 min is foreseen. In the draft standards the capacity test is preceded by a standard cycle. However, this is already done at the end of the preconditioning test. Only re-charging the cell is applied to be sure that it is completely full. In the test standards, the charge rate is limited to only the recommended one by the manufacturer. It is suggested to use the same charge rate as the discharge rate until the maximum allowed by the manufacturer is reached.

The broad range of discharge rates reflects both the (P)HEV and BEV applications. It also allows a good comparison of the available cells given that, except the NiMH-cell, they all accept 5 C discharging and many 10 C. Including a C-rate lower than 1 C in the capacity test is also good to well establish the 1 C capacity, in case the given capacity by the manufacturer does not correspond well to the 1 h discharge capacity.

The test set-up allows to establish the Peukert constant and the 1 C capacity, according to:

$$1\,C\quad \text{capacity} = (\text{Peukert}\quad \text{capacity})^{1/\text{Peukert}\quad \text{constant}}. \qquad (1)$$

If the calculated 1 C capacity differs more than 5% from the one given by the manufacturer (called I_T) than the calculated 1 C value will be employed for the subsequent tests.

Unlike the original tests, the discharge rates are arranged from high to low. If the test is started up in the morning, the operator can be present during the in principal most dangerous current rates. If one would start with the low current rate, the maximum rates occur somewhere in the night. This order is also practical for measuring the heating of the cells, what is discussed below. The drawback of this arrangement is that any ill effect of high pulse rates has an influence on the results of low rate discharges. However, by staying within the specifications of the manufacturer and doing the complete test only once, an ill effect is not ought to happen. It can be detected by including a standard cycle after each test and comparing the capacity with the previously measured capacity to track the cell's behaviour.

Charging a battery consists of a constant current phase (CI) and a constant voltage phase at which the voltage is kept at the maximum allowed one (CV). This second phase is ended when the current drops to 0.01 C for all cells. The standards prescribe the final current as defined by the manufacturer. This varies from 0.05 to 0.01 C. In addition to the standard charge that ends the capacity test the CV charging part is enlarged until 0.001 C or 8 h in order to detect whether a leakage current would exist. For nickel metal hydride cells this way of charging is not valid since these cells are charged at constant current until the voltage decreases after reaching a maximum [19,20].

During the highest discharge rate the heating of the cell can be monitored with help of a thermal camera in order to get insight in the heating behaviour and the heat distribution. Although thermocouples are used to monitor the cell temperature, this does not cover the temperature at all places over the cell as can be seen in Fig. 5. If the cell temperature becomes higher than allowed, then active cooling is needed with help of strong ventilators. Also the cell expansion can be measured (manually).

In order to test NiMH cells the C-rates have to be adapted since otherwise only 3 current rates are possible (0.33 I_T; 1 I_T; 2 I_T). Assuming that they are used in practice within a band of around 20% depth of discharge, the C-rate is divided by 5.

The test duration is about 45 h.

5.3. Dynamic discharge performance test (DDP)

The dynamic discharge performance test is taken from IEC 61982-2. It should simulate the BEV behaviour. It consists of four steps that are repeated until the cell reaches the minimum allowed voltage. The cell is charged at 1 C and the cycle is repeated 3 times. The four steps consist of:

- 1.6 C discharge during 10 s;
- 0.4 C discharge during 20 s;
- 0.8 C charge during 5 s;
- pause of 25 s.

This means that the average discharge rate is 0.33 C.

Originally, the discharge rates have been expressed in C3-rate, i.e. 5.2, 1.3 and 2.6, respectively. The suggested schedule is expressed in C-rate after rounding the figures while maintaining the ratio between each other.

This test yields a net discharge capacity. Also the average discharge voltage can be calculated by averaging all voltage data points. The energy density can be calculated, based on the net discharge capacity expressed in W h and the cell weight.

The test duration is about 16 h including a final standard cycle.

5.4. Integrated pulse test

The integrated pulse test is based primarily on the power density test from the IEC 62660-1 standard. Calculations have been added as executed in the FreedomCAR HPPC test and the power and internal resistance test in the ISO/DIS 2405-1. It consists of a series of 8 discharge and charge pulses that are executed at 5 SOC levels: 80, 65, 50, 35 and 20%. After the pulse series at a SOC level, the cell is discharged to the next SOC level. From the test in the previous section it became clear that the rest period between the discharge and charge pulse can be restricted to 40 s. This time should be until the cells are less than 2 °C warmer than room temperature. In practice this never happened. The rest period after a charge pulse should be taken 10 min.

The pulses are based on the integration of the two pulse trains mentioned in IEC 62660-1 with the addition of a pulse discharge/charge combination at the maximum charge rate. This results into 8 pulse pairs. The pulses of 10 s each have the following amplitudes: 0.33 C; 1 C; 2 C; 5 C; 10 C; 20 C; max. charge current and max. discharge current. It is visualised in Fig. 6. If the maximum allowed charge pulse is lower than the discharge pulse, the charge duration is increased proportionately to maintain the same SOC level, the so-called charge sustaining operation. In this way the efficiency of the discharge and charge pulse combination can still be calculated. If the charge voltage exceeds the maximum allowed

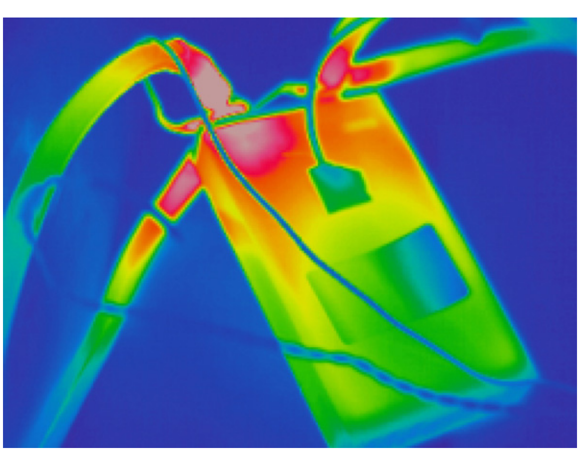

Fig. 5. The temperature is not homogeneous at the outside of a cell. The rectangles on the cell are due to stickers attached the cell, of which one is holding a thermal couple.

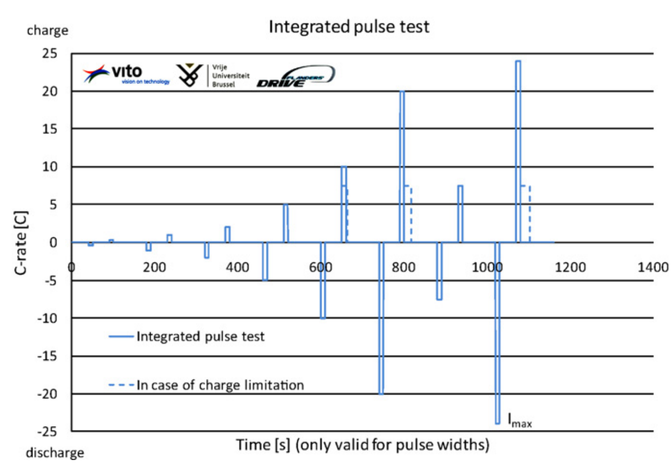

Fig. 6. Integrated pulse test. The pulse period is 10 s or increased in case of charge limitation. The time between a discharge and charge pulse is 40 s and the interval after a charge pulse is 10 min.

voltage, the maximum allowable voltage is imposed resulting in a lower current.

According to the energy efficiency test in the ISO/DIS 12405-1, the test data can be used to calculate pulse efficiencies. This follows from the discharge energy divided by the charge pulse energy. The power and internal resistance test in the same standard calculate power and internal resistance values per pulse at 0.1 s; 1 s; 2 s and 10 s. The resistance follows from the voltage drop (or increase for the charge pulse) divided by the pulse current. The power value follows from the voltage multiplied by the pulse current. A usual calculation is the power density that follows from the maximum pulse rate at 50% SOC, e.g. in [8]:

$$\text{pulse power density} = \frac{I_{\max}\,[\mathrm{A}] \cdot U_{(50\%\,\mathrm{SOC},\,10\,\mathrm{s})}\,[\mathrm{V}]}{\text{cell weight}\,[\mathrm{kg}]} \tag{2}$$

To be able to compare pulse power densities it is interesting to add the power density for a 10 C pulse, since this pulse strength is attainable for most cells in this test.

The data of the maximum discharge and charge pulse at each SOC level can also be used to fit the FreedomCAR model [18]. If this fitting is an important item of the cell characterisation, then the pause period between the discharge and charge pulse may be increased to 10 min, what followed from the test in the previous section. The 90% and 10% SOC level may be included, like in the FreedomCAR HPPC test, since the cell parameters deviate often more at the ends of the SOC range. However, at 90% SOC the charge rate should be limited to avoid reaching the maximum allowed cell voltage. Analogously, at 10% SOC the discharge rate should be limited to avoid reaching the minimal allowed cell voltage.

To test NiMH cells, the C-rates have to be adapted since otherwise only 3 pulses are possible. Assuming that they are used in practice within a band of approximately 20% depth of discharge, the C-rate is divided by 5.

A pulse series of the 8 proposed discharge and charge pulses may take 110 min. The test duration with 5 SOC levels and a standard cycle at the end is about 19 h.

6. Conclusion

In the article the six main international (draft) standards to characterise battery cells have been discussed. The test methods have been confronted with the 4 intended vehicle applications, ranging from hybrid electric cars up to battery electric cars. The existing capacity tests ignore that cells can be charged at several current rates. This is, however, of interest for e.g. fast charging and regenerative braking. With respect to the pulse tests it is found out that an integration could be made of prescribed test methods to fit all of the intended applications. The integration is also necessary to speed up the tests. This needed an adaptation so that the discharge and charge pulses are almost equalised in terms of capacity (charge sustaining operation). This adaptation does not have a negative aspect for fitting the measurements with the FreedomCAR battery model. The tests can be used both for lithium-ion and nickel metal hydride cells provided that the current rates are divided by 5 for the last one.

It is esteemed that it is better in terms of comparability to base pulse rates on derived 1 C capacities (the capacity that equals with a 1 h discharge time) that can be estimated from a capacity test at several current rates, rather than just on the capacity as indicated by the manufacturer (called I_T in the article).

None of the test standards describe the slope of the pulses. In this way the flank depends on the quality of the cell test machine and can consequently vary in practice between 1 ms and 1 s.

It is hoped that in sharing the enhanced cell characterisation test method with the scientific community, cell testing can become more powerful and less time consuming.

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Glossary

C-rate: current relative to the capacity of a cell or battery. The capacity is the 1 h capacity, i.e. the capacity derived from of a full discharge in 1 h (C or A Ah^{-1})
C3-rate: The capacity is the 3 h capacity, i.e. the capacity derived from of a full discharge in 3 h (C3)
DOD: depth of discharge (%)
BEV-PC: battery electric personal car
HEV-B: hybrid electric bus
HEV-PC: hybrid electric personal car
HPPC: hybrid pulse power characterisation test
I_{max}: maximum allowed current by the manufacturer
I_T: current relative cell or battery capacity as declared by the manufacturer (I_T or A Ah^{-1})
LFP: lithium-ion iron phosphate cell
NCA: lithium nickel cobalt aluminium oxide cell
NiMH: nickel metal hydride cell
NMC: lithium-ion nickel cobalt manganese oxide cell
OCV: open circuit voltage
PHEV-PC: plug-in hybrid personal car
RT: room temperature
SOC: state of charge (%)