Characterization of Lithium-Ion Silicon-Graphite 18650 cells under Driving Cycles

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***Abstract*—Next-generation Electric Vehicles (EVs) will demand higher range, longer lifespan and better reliability than current EVs. In order to achieve that, the improvement of the energy storage system is crucial. EVs generally use lithium-ion batteries (LIBs) as their energy storage system. The development of new electrode materials in the last few years, in particular the use of silicon-graphite negative electrodes, promises an increase in energy density and, therefore, potentially higher range and lifespan on EVs. The proper evaluation of this battery technology is fundamental to assure the desired levels of energy density without a notable performance loss. In this paper, we propose a characterization method for LIBs with silicon-graphite electrodes, on which the batteries are tested under various EV standards, such as the recently enforced Worldwide Harmonized Light Electric Vehicle Test Protocol (WLTP)**

Keywords—Electric Vehicle (EV), Lithium-Ion Batteries (LIBs), Silicon-Graphite Electrodes, Driving Cycles, Dynamic Stress Test (DST), Worldwide Harmonized Light Electric Vehicle Test Protocol (WLTP)

I. INTRODUCTION

The Electric Vehicle (EV) is one of the fundamental elements of the forthcoming technologic development for the next years. It is an important field of research which has grown notably in the last few years [1], as one of the main goals of the European Union is not to depend on fossil fuel importation [2].

The demand for EVs has notably increased in the last years. However, there is still a low penetration of EVs in the road transport. The two main factors that are limiting the development of the EVs are their range and their cost [3][4].

EVs are complex systems which integrate different subsystems, and one of the most important is the battery system, which is the main energy source for the vehicle, as it has a notable influence in the range and cost of the whole vehicle. Nowadays, most of the commercial EVs are using lithium-ion batteries (LIBs) as their energy storage system [5]. LIBs have notable advantages over other energy storage technologies, such as high specific energy and power, long cycle life, high efficiency, no maintenance and their high current capability [6].

However, their performance is still not good enough for the EV to fully replace conventional vehicles [7]. Higher energy densities and lower costs are needed. In order to improve these factors, the main development area for LIBs is the electrode materials. Historically, negative electrodes are made of graphite intercalation compounds (GICs), on which lithium ions are inserted and de-inserted during charge and discharge [8]. When fully charged, a GIC electrode can only hold one lithium ion per six carbon atoms (LiC_6). This limits the practical energy density for LIBs. For this reason, other materials are being developed for their use as negative electrodes, such as lithium titanate oxide or silicon. Lithium titanate is not the optimal solution because its energy density is lower than GIC. Silicon is a more promising material for negative electrodes, because it has a much higher energy density than GIC. When fully charged, 5 atoms of silicon are able to hold 14 lithium atoms ($Li_{14}Si_5$). This allows silicon electrodes to have an energy density six times higher than GIC electrodes [9].

For this reason, it is expected that the next generation of EVs will be using LIBs with silicon as negative electrode material. However, silicon has a notable drawback as a LIB electrode, which is the volume changes it experiences when it is charged and discharged. The volume changes can be as high as a 280%, which is impractical for a LIB [10]. The solution that is being implemented is the use of small silicon particles in conventional

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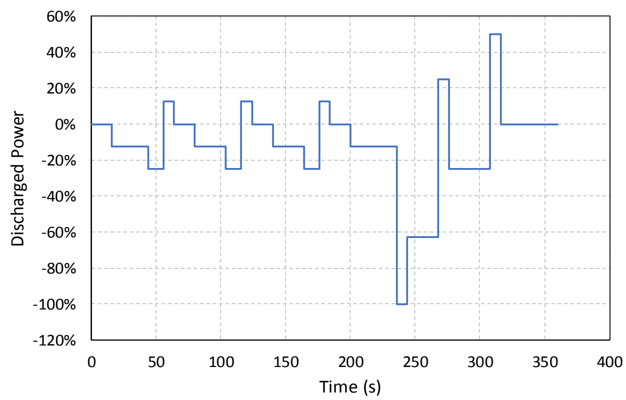

Fig. 1. Dynamic Stress Test (DST) profile

GIC electrodes, which is denoted as silicon-graphite electrode. This type of composite material can achieve higher energy densities without important volume changes [11].

In the last few years, the first commercial LIBs with silicon-graphite electrodes have entered the market. Most of them are using NMC as positive electrode material, a composite of nickel, manganese and cobalt. Silicon-graphite cells are using NMC positive electrodes with a high nickel percentage. This allows higher energy densities to be achieved [12]. The European Union Commission expects that this type of electrode materials will be used for EV batteries for the next 5-10 years [13]

It is crucial to properly evaluate the cells that will be used in the future EVs, as it is important for them to be reliable and have a long range and lifespan. To the best of our knowledge, commercial silicon-graphite cells have not yet been evaluated under electric vehicle applications.

In order to evaluate a LIB for an EV application, it has to be tested under conditions that are very close to their use in a real EV. Different standards have been proposed on the literature, most of them based on the regular driving cycles that are used to evaluate conventional cars range. Since the late 1990s, the United States Advanced Battery Consortium (USABC) has established a standard test for EV batteries, known as dynamic stress test (DST), which is a simplification of the American Federal Urban Driving Schedule (FUDS) [14]. It has been accepted as an EV testing standard for years. However, nowadays more demanding standards are being stablished. In Europe, the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) is mandatory for all new vehicles since September 2019 [15]. For this reason, this test standard should also be conducted at laboratory level for evaluating LIBs for EVs.

This paper presents an evaluation program for commercial LIBs with silicon-graphite negative electrodes, focused on the state-of-health evaluation under charge and discharge regimes that resemble the typical use in an EV application. Cells from two different manufacturers have been acquired in order to compare their performance under typical EV profiles. Both DST and WLTP are used, in order to stablish a comparison between both standards.

II. EV BATTERY TESTING

The range and performance of vehicles is usually measured with test based on driving cycles. It is a series of data which represents the evolution of the speed of a vehicle against time [16]. Several standards have been used for this purpose, such as the New European Driving Cycle (NEDC), the Federal Urban Driving Schedule (FUDS) or the Worldwide Harmonized Light Vehicle Test Procedure (WLTP).

In the case of EVs, the energy storage system must be evaluated with close-to-real charge and discharge regimes [17]. The best way of doing this is to translate a driving cycle into a power vs time data series, which is then applied to the energy storage system via an automated testing machine. However, the relationship between an EV speed and the energy storage system power consumption can be complex. Factors such as the vehicle weight, terrain slope and aerodynamics play an important role in the energy consumption. Vehicle models are needed in order to obtain a power profile from a driving cycle [18].

As many factors can have a notable influence in an EV energy consumption, different driving cycles will have a different impact in the energy storage system. A driving cycle which is taken from a mountain road with high slopes and another which was taken in the city of Barcelona will suppose a different energy and power demand from the energy storage system. For that reason, the more recently developed driving cycles, such as the WLTP, have been obtained from statistic data which resembles the modern roads and driving styles.

In order to evaluate the batteries under study, we have proposed the use of two different standards.

1. Dynamic Stress Test: This is the most widely used test for evaluating batteries for EVs. Stablished by the USABC, the test is based on a power profile which can be scaled to any desired specific power. The test profile is shown in Figure 1, where the 100% level is the desired specific power.
2. Worldwide Harmonized Light Vehicle Test Procedure (WLTP): As it is the new standardized driving cycle for all European vehicles, it is important to stablish a comparison between it and the current standard. Unlike DST, WLTP is not defined as a power profile, it is a regular driving cycle defined as speed vs time. In one of our last work, we developed a model to convert driving cycle data to electrical power, based on the characteristics of a reference test vehicle. For this work, we have used the data from the Tesla Model 3 and translated WLTP speed to power. The obtained profile has been defined for a maximum power which can be set as the experiment needs, like DST. The WLTP cycle is shown in Figure 2, and the derived power consumption from our model is shown in Figure 3.

III. EXPERIMENTAL PROCEDURE

A batch of two different types of 18650 cells with silicon-graphite negative electrodes was acquired for their evaluation. Both cell types also share a similar NMC 811 positive electrode. The characteristics of the cells are shown in Table 1.

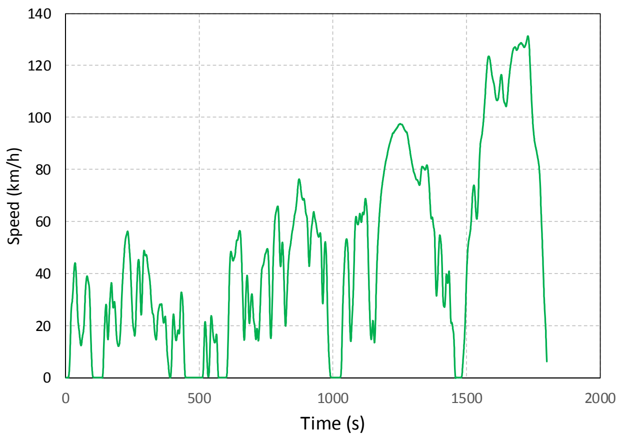

Fig. 3. Class-3 Worldwide Harmonized Light Vehicle Test Procedure

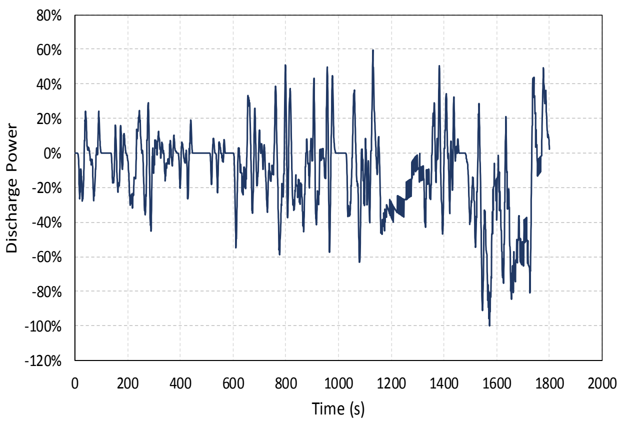

Fig. 4. WLTP demanded power for a Tesla Model 3

The main goals of the proposed test program are to characterize and evaluate the aging and performance of both types under an EV application, using the two test standards mentioned in the previous chapter. Once the cells are received from the distributor, a commissioning procedure is run, on which the cell voltage, weight and dimensions are measured. After commissioning, a conditioning test is run, on which several charges and discharges at low current regimes are run to obtain the first capacity references. Each time that a 5% capacity loss is detected, Reference Performance Tests (RPTs) are run in order to evaluate the state of health of the cells. These RPTs include several complete charges and discharges, as well as an electrochemical impedance spectroscopy (EIS) test to evaluate the impedance characteristics of the cells. The test program is shown in Figure 4.

The aging schedule consists in repetitions of the driving schedule on loops, ending the cycle when the lower voltage limit is reached for each cell type (i.e. 2.50 V for cell type 1 and 2.65 V for cell type 2). Then, the cells are charged under their respective standard schedule and the driving cycle is applied again, on a loop. Every 50 cycles, a reference charge/discharge test is run. If a capacity loss of at least 5% is detected on discharge, a RPT is run before continuing cycling. Charge current is limited to 1C for both cell types as the manufacturers don't recommend higher charge currents. Discharge currents are

TABLE I. CHARACTERISTICS OF THE STUDIED CELLS

Cell	Nominal Capacity	Nominal Voltage	Maximum charge	Maximum discharge
Type 1	3500 mAh	3.635 V	3.4 A	10.0 A
Type 2	3400 mAh	3.600 V	2.0 A	13.0 A

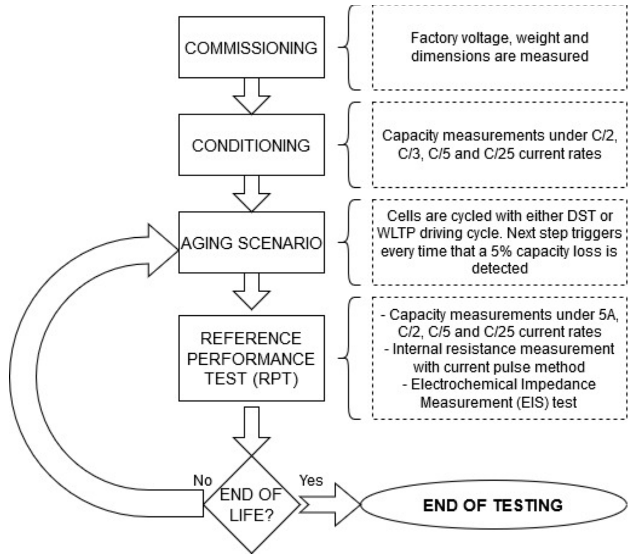

Fig. 2. Complete test procedure for the evaluation of the cells under study

not limited, as the highest expected currents fall into both cells' safety limits for discharge.

IV. RESULTS

The commissioning testing indicated that the cell batch has a low dispersion. Factory voltages only show a standard deviation of 1 mV for the cell type #1 and 3 mV for the cell type #2. In terms of weight, standard deviation is 0.36% for the cell type #1 and 0.08% for the cell type #2.

Conditioning tests revealed the charge and discharge voltage profiles for both cell types. Figure 5 shows the discharge profiles at the nominal discharge rate (C/5), and Figure 6 shows the charge profiles at the nominal charge standard, which is a CCCV charge where the constant current phase is at C/2 rate and the constant voltage phase is at 4.2 V, which are maintained until the cut off current is achieved (50mA for cell type #1 and 68mA for cell type #2).

Figure 7 shows the impedance spectrum for both cell types, with real component in axis X and minus the imaginary component in axis Y.

The first stages of EV cycling allow a comparison between the two standards and the two different cell types under study. Both cell types were able to complete a total of 25 DST cycles and 6 WLTP cycles before their respective lower voltage limit was reached. Figure 8 and 9 show, respectively, a DST and a WLTP cycle applied to the tested cells, in terms of voltage and current. Finally, Table II shows the average charged and discharged capacity and energy for both cell types and both test regimes at the first stage of cycling. Table III shows the average

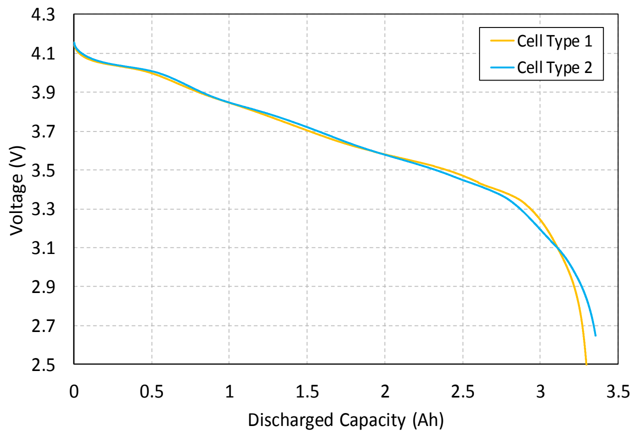

Fig. 5. Discharge curves for both cell types under C/5 rate

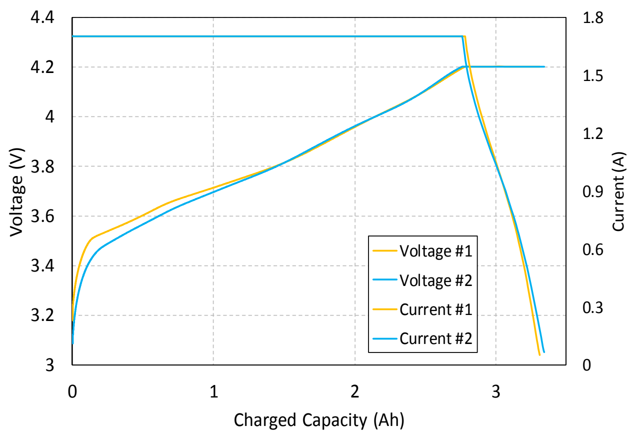

Fig. 6. Charge curves for both cell types under standard charge protocol

energy efficiencies and maximum cell temperature increase during cycling for both test regimes. Energy efficiencies are calculated as the ratio between discharged and charged energy for each full cycle, which is composed of a full standard charge and the repetition of the driving cycle until the lower voltage limit is reached.

V. Discussion

Even though both cells share similar chemistry, as stated by their respective manufacturers, small differences can be observed in the charge and discharge curves. It is notable that the type #1 cell capacity is clearly lower than the stated nominal capacity. In average, the type #1 cells have obtained a capacity of 3292 mAh under C/5 rate (nominal), which is 6% lower than the nominal capacity (3500 mAh). On the other hand, the type #2 cells averaged 3367 mAh, much closer to the stated nominal capacity (3400 mAh).

Energy efficiencies were calculated as the ratio between the discharged and charged energy for each cycle. Under standard rates, both for charge and discharge, cells from type #1 averaged 93.35% efficiency and type #2 averaged 93.79%. These values are slightly lower than other cell types tested in our laboratory. For example, LFP A123 cells have energy efficiencies around 97%. The energy efficiency will be tracked as the cells are tested under the driving cycle profiles.

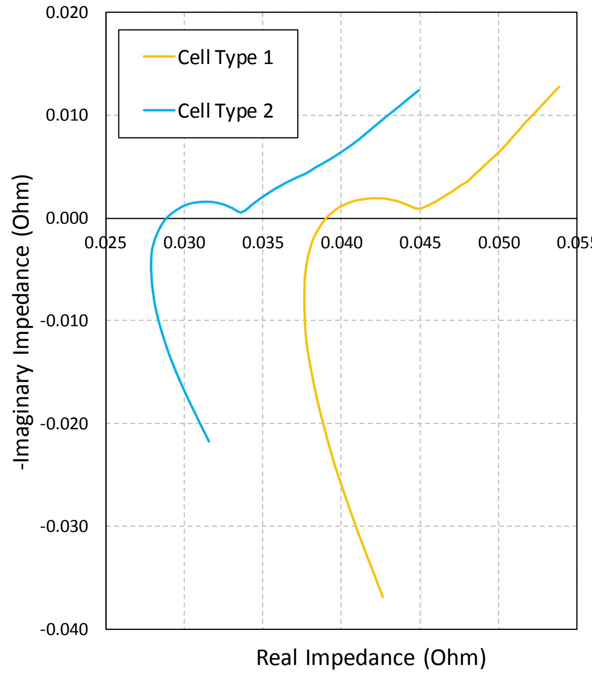

Fig. 7. Electrochemical Impedance Spectrum (EIS) for both cells under study

EIS testing revealed that the impedance from the cell type #1 is clearly higher than the impedance from the cell #2. Both spectrums share a similar shape, so both cells have similar dynamic behavior, but cell type #1 shows higher ohmic resistance at all frequencies.

When comparing both test regimes, as the WLTP cycle represents very realistic conditions and DST is a synthetic, simplified cycle, WLTP demands higher and more frequent current swings, quickly alternating charges and discharges. As shown in Table II, WLTP demands more charging than DST during a whole cycle of repetitions (i.e., until lower voltage cut is achieved), representing higher energy recovery from vehicle braking.

Both driving cycle regimes have a different profile duration, as DST is much shorter than WLTP. However, in terms of number of loops achieved without achieving the lower voltage limit, both cells completed exactly the same number of loops for each driving cycle. At factory status, both cells have a much similar performance in terms of driving conditions. As cells are further cycled, it will be interesting to see if any cell type loses performance before than the other and to identify the cause using the proposed diagnostic techniques.

When comparing the total amounts of capacity and energy charged and discharge during the EV testing, as WLTP demands more charge time, higher discharge capacities can be achieved. In particular, cells from type #2 showed a higher discharged capacity and discharged energy increase when comparing WLTP and DST cycling. This could mean that cells from type #2 have had a higher charge acceptance than cells from type #1.

Finally, comparing the values from Table III, it is shown that the temperature increases due to EV testing in both cells is not remarkable, as standard constant current testing on the cells have

TABLE II. CHARGED AND DISCHARGED CAPACITIES AND ENERGY DURING EV CYCLING

Cell	DST			
	Ah Charged	*Ah Discharged*	*Wh Charged*	*Wh Discharged*
Type #1	0.430	3.498	1.614	12.419
Type #2	0.435	3.506	1.625	12.505
Cell	**WLTP**			
	Ah Charged	*Ah Discharged*	*Wh Charged*	*Wh Discharged*
Type #1	0.804	3.805	3.063	13.572
Type #2	0.861	3.931	3.255	14.059

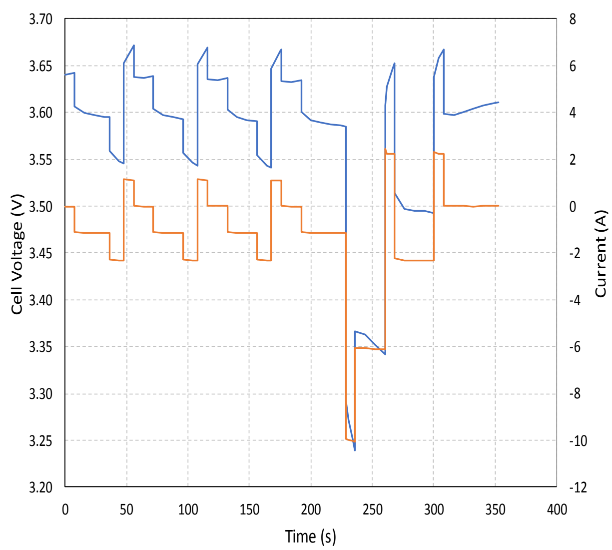

Fig. 8. DST cycling applied to one of the tested cells. Blue data is the cell voltage (left axis) and orange data is the charged current (right axis)

shown temperature increases higher than 10°C. It is interesting that the energy efficiency for cell type #1 falls from 94.2% in DST to 91.8% in WLTP, while for cell type #2 it only falls from 92.1% to 91.7%. This shows again that WLTP cycle is more demanding than DST, as lower efficiencies are shown for the very same peak power level and the very same batteries. The fact that cell type #2 has a lower efficiency loss is also an indicator of a better performance, and it sums up with the higher achieved discharged energy for that cell type. Behavior under DST is similar for both cell types, the performance difference is only noticeable under WLTP cycling.

VI. CONCLUSIONS AND FUTURE WORK

It is expected that the next generation of EVs will be using lithium-ion batteries with new electrode materials, including silicon-graphite negative electrodes and nickel-rich NMC positive electrodes. For this reason, it is important to evaluate how that chemistry behaves under typical EV stress, both in performance and aging terms. A test program has been proposed, in which two different standards for EV energy storage systems are compared. The DST standard is compared to the most recent WLTP standard, mandatory in the European Union since September 2019. The test program includes

TABLE III. TEMPERATURE INCREASE AND ENERGY EFFICIENCY DURING EV CYCLING

Cell	DST		WLTP	
	Temp Incr (°C)	*Energy Efficiency*	*Temp Incr (°C)*	*Energy Efficiency*
Type #1	6.113	94.2%	5.941	91.8%
Type #2	5.500	92.1%	6.011	91.7%

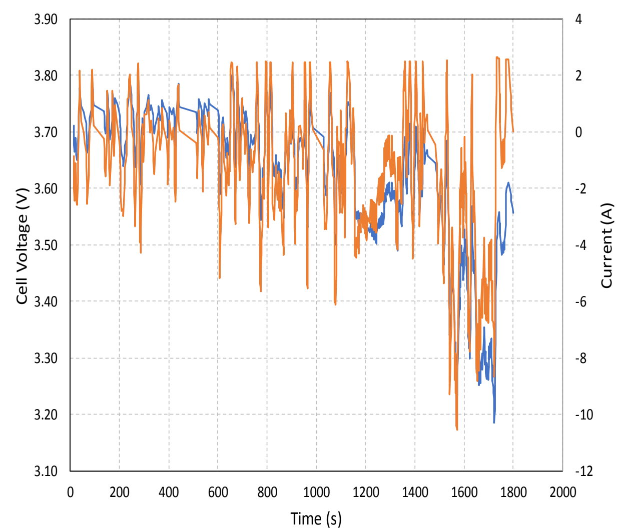

Fig. 9. WLTP cycling applied to one of the tested cells. Blue data is the cell voltage (left axis) and orange data is the charged current (right axis)

characterization tests that evaluate capacity and impedance of the battery cells. Two different types of 18650 cells have been evaluated under the proposed test program, and their factory performance has been measured, detecting the first differences between them.

As August 2020, only the first stages of cycling have been completed and presented in this paper. In the upcoming months, further cycling will be done. The proposed framework and analysis techniques will be used throughout cycling as an indicator of cell performance.

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