EVTC

Electric Vehicle Transportation Center

Test Plan to Assess Electric Vehicle Cell Degradation under Electric Utility Grid Operations

Matthieu Dubarry
Hawaii Natural Energy Institute

University of Hawaii at Manoa
1680 East West Road, POST 109
Honolulu, HI 96822
E-mail: matthieu@hawaii.edu

Submitted to:

Dr. David Block
Florida Solar Energy Center
University of Central Florida
1679 Clearlake Road
Cocoa, FL 32922
E-mail: block@fsec.ucf.edu

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HNEI
Hawai'i Natural Energy Institute
School of Ocean and Earth Science and Technology
University of Hawai'i at Mānoa

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1. Abstract

This report details the testing plan that will be used by the Hawaii Natural Energy Institute (HNEI) to evaluate Electric Vehicle (EV) battery durability and reliability under electric utility grid operations. Commercial EV battery cells will be tested in order to assess the impact of vehicle to grid and grid to vehicle applications on cell degradation. The plan also includes testing other usages associated with EVs under grid operations such as the impact of charging level and charging habits. The choice of duty cycles, real driving cycles as well as constant power for the vehicle to grid charges and discharges will be detailed and justified. This report also introduces the application of design of experiments techniques for both the cycling and the calendar aging study. They will allow us to derive the maximum amount of information and ensure experiment consistency.

2. Introduction

EVs and renewable energy sources offer the potential to substantially decrease carbon emissions from both the transportation and power generation sectors. Mass adoption of EVs will have a number of impacts, including the ability to assist in the integration of renewable energy into existing electric grids. This assistance can be used to provide energy to the grid (Vehicle to grid, V2G) and/or to remove energy from the grid (grid to vehicle, G2V). The potential benefits of V2G and G2V have been heavily investigated in recent years [1-5]. One key parameter to weight in the applicability of V2G or G2V is the degradation of the batteries induced by the additional charge and discharge cycles. Indeed, the success of V2G/G2V strategies will depend on consumer acceptance and desire to participate in the program. On the consumer side, it is essential to compare the reward – the financial gain from "selling" some of their EV battery capacity to the grid utility – to the risk – the potential for accelerated degradation of the battery thereby reducing lifetime. The literature on the subject is limited as most studies use essentially unreliable battery models to address the question [6-10]. Only one study by Peterson and Whitacre in 2010 [11] appears to address these issues via testing commercial Li-ion batteries. They concluded that constant current V2G had little effect on the cells, but unfortunately the battery cells tested were Lithium Iron Phosphate, which are no longer used in commercial EVs. Also only one set of conditions was considered, thus the combined effects of V2G and G2V strategies was not discussed.

V2G and G2V strategies are thought to be useful to supplement the power used by a building; provide ancillary services and emergency support to the power grid; smooth the variable output from electricity generators using renewable sources; and utilize surplus energy when supply exceeds demand [6]. These four applications will lead to different usage of the batteries and they need to be tested separately. As part of the US Department of Transportation funded Electric Vehicle Transportation Center (ETVC), HNEI has partnered with the Florida Solar Energy Center to perform laboratory testing on commercial Li-ion cells to evaluate the impact of V2G and G2V strategies on the cells. In a first approach we will only consider the ancillary service for V2G and the surplus energy for G2V. This is because we are looking at the effect of EVs on the full island electric grid and not at the building and/or generating unit level. Those might be considered in the follow up studies in years 3 and 4.

In order to assess the impact of the V2G/G2V strategies on the cells it is important to take into consideration all the different ways the cells can be used. Battery degradation is path dependent, so it is possible that in some cases harder usage of the cell still results in lower degradation [12]. As an example, performing V2G during peak time will delay the battery charge and it is therefore important to test the effect of the delay by itself. The delay might have an effect because one of the major contributors to degradation is calendar aging, i.e. the degradation the cell undergoes while resting. This degradation is state of charge (SOC) dependent and delaying implies that the cells are resting before the charge and not after, thus at a lower SOC which should be beneficial. To take those issues into account, we are planning to first investigate the effect of V2G/G2V combined with different charging habits (1 or 2 charges a day, immediate or delayed charging) and different charging currents (level 2 or fast charging). Moreover, the effect of calendar aging at different temperatures will also be investigated in another set of experiments.

3. Experimental Protocols

HNEI has extensive experience designing test protocols for testing of batteries ranging from small watt size cells to grid connected megawatt energy storage systems. A good test protocol should yield all the information necessary to understand cell performance, assess its degradation as a function of time and operating conditions, and be reproducible for comparisons between cells.

Under this task, HNEI has developed a detailed test plan and protocols to assess the performance and reliability of the cells under different testing conditions. The overall testing consists of the 4 elements summarized in Figure 1:

- An initial test to verify the cell meets its specifications, to assess the cells quality compared to the rest of the batch, and to validate the test results against those of the supplier,
- A reference performance test (RPT) at regular intervals to assess the evolution of battery performance over time,
- A repetitive duty cycle that consist either of EV driving data, charging and eventual V2G additions or of calendar aging.
- An end-of-test evaluation to provide detailed characterization of cell performance at the end-of-test and insights into the degradation mechanisms.

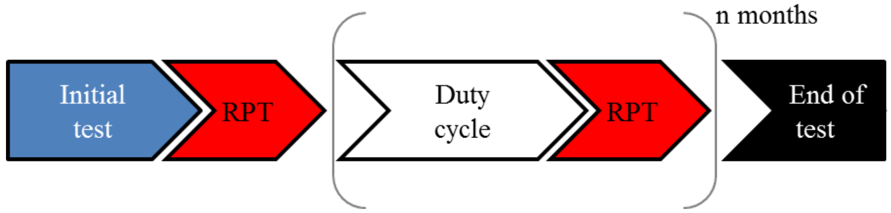

Figure 1: Testing sequence within proposed procedures

Each of these four procedures is described below:

3.1. Initial, RPT, and End-of-Test Protocols

Initial Test. The initial test will be designed, from our previous experience, to assess key battery metrics including active material content, rate capability and resistance. This procedure is extremely important to assess the initial cell performance and identify cell-to-cell variation problems at an early stage. Details are presented in appendix A.

Reference Performance Test. The reference performance test will be performed on a regular interval, typically every month, to quantitatively measure battery performance, including capacity fade and state of health, which impact the battery's ability to deliver the power and energy required in the duty cycle. Comparison of these direct measures as well other factors such as capacity retention, and energy efficiency will enable quantification of the degradation into three categories; loss of active material, loss of reactant and kinetic degradation. In this test, the cell is tested against a range of currents, from low to high, to assess the thermodynamic and kinetic changes with aging. (Details in appendix A).

End-of-test evaluation will be conducted to assess the final state of the battery and will include some post-mortem characterization of the cells if judged necessary by HNEI. HNEI's facility offers the use of an argon-filled, atmosphere-controlled 'glove box' where the cells can be safely disassembled and the individual electrodes/components studied via microscopic or electrochemical methods. If necessary, samples could be prepared, sealed and sent to other institutions for additional characterizations unavailable on campus (X ray diffraction and spectroscopic surface analyzes).

3.2. Duty Cycle for Cycling Experiments

The duty cycle for cycling experiments is composed of 6 different steps (Figure 2): 2 driving and 4 parked steps. The 2 driving steps corresponds to the commute the EV would perform every day to and from work. This will be a constant in this initial study. The parked steps are the parameters that will be varied in this study. The parked steps can be a rest period, a V2G period or a charging period. The different protocols are detailed in the following sections.

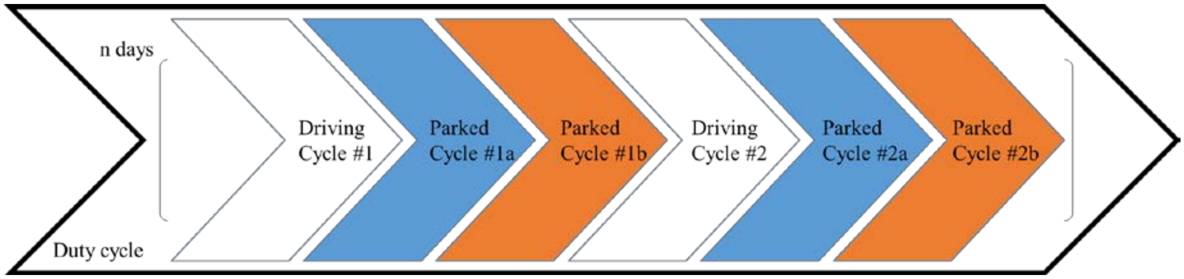

Figure 2: Details on duty cycle

Driving Cycle Protocol. As mentioned in the introduction section, the battery degradation is extremely sensible to the duty cycle. In order to ensure that our study will apply to EVs, the duty cycle we will used will be based on real driving data. Using scaled-down real data is possible since the HNEI battery testers allow direct testing of second by second duty cycles directly.

The selected trip data was taken from an HNEI, in-house database. In the early 2000s, HNEI was involved in a 2 year EV data collection program [13-15] which resulted in over 100,000 km (over 60,000 miles) being logged. Several commuting trips were identified that would be ideal for this study. Although the average American drives 50 km (approximately 31 miles) a day, we chose a slightly shorter trip around 30 km (approximately 19 miles) round trip (Figure 2). Data from this trip was chosen because of its diversity. According to our classification method [13-15], this drive had every kind of road condition from stop and go driving to highway driving, thus making it efficient to test as a representative trip. This trip was also chosen because we have data for about 20 round trips that are to be used in possible follow up studies.

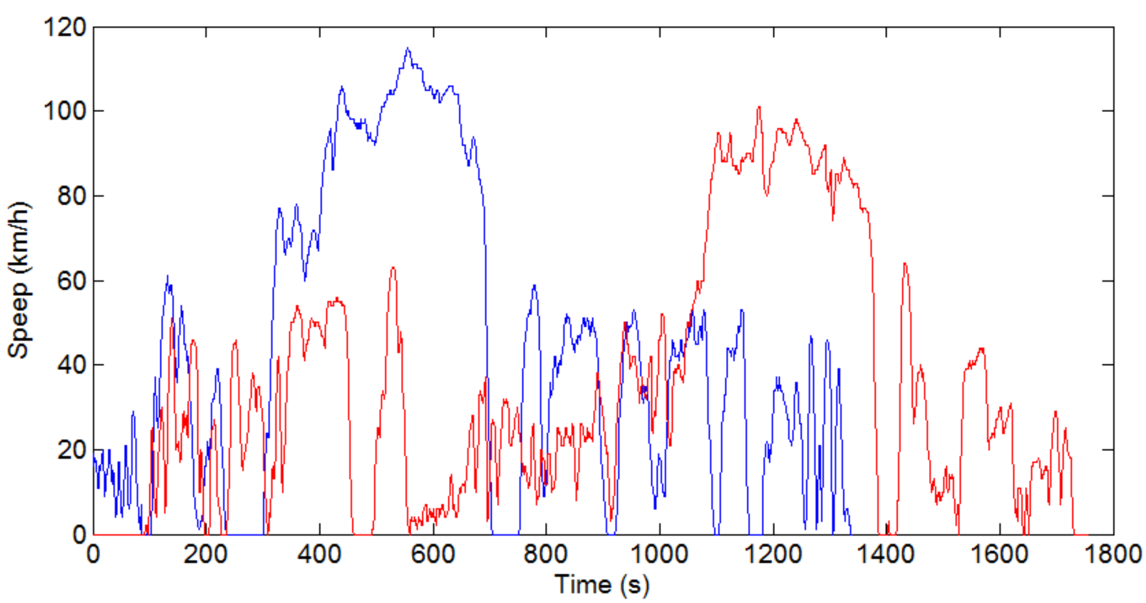

Figure 3: Example of daily EV drive (commute to work in blue, return in red).

V2G Protocol. As mentioned in the introduction, for this first round of testing, we chose to investigate only ancillary service for V2G strategy and the surplus energy strategies for

G2V. In these scenarios, the battery pack is used to give or store energy from the grid and not for frequency response or voltage support. For the selected application, the duty cycle will likely result in inputting/outputting a constant power profile from the cells. This is due to the fact that the size of the batteries are several orders of magnitude smaller than the grid power, thus applying a complex duty cycle will have no effect at all. The chosen rate will be scaled based on the most popular vehicle battery pack size, in the 25 kWh range, and the typical infrastructure available in homes (240V, 30A) [11]. In this case, the home charger can only maintain at most 7.2 kWh of energy transfer thus recharge less than one third of the capacity every hour. In order to get close to – but under – that value during our testing, the constant power rate chosen for V2G simulation will be one quarter of the rated power (P/4).

The duration of the V2G step will be based on the grid needs and on what most benefits the customer. Figure 4 presents an example of an hourly price of electricity on an open market [2]. Although the time of the peaks might shift from state to state, we believe that the overall shape of the curve is representative of an average grid in North America. There are two price peaks where customers will benefit in selling their electricity, around noon and in the early evening; 10:30 to 11:30 and 20:30 to 21:30 in this example. Therefore a V2G user will maximize the benefits by selling electricity during these 1 hour periods. According to this observation, we will apply V2G current for 1 hour steps in this study. Conversely, maximum G2V benefits will be when electricity is the lowest.

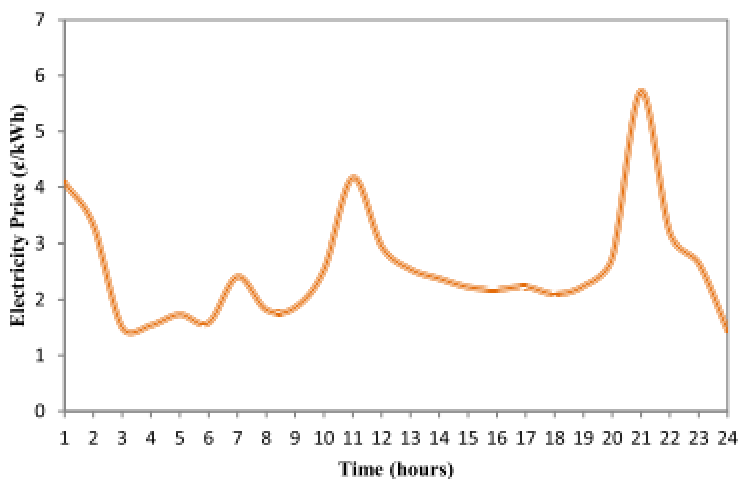

Figure 4: Example of the hourly electricity price of open market from [2]

Charging Protocol. Typical home battery chargers can usually charge the EV battery packs in up to 21 hours for level 1 charging and in about 8 hours for level 2 charging [16]. The Nissan Leaf onboard charger allows a full charge in about 4 hours [17] with level 2 charging. For this set of experiments, we will assume that most people invested in the 8 hour level 2 charging station, we therefore selected an 8 hour charge, focusing on level 2 charging. If the vehicle is plugged in during the day, we will assume it can access a public battery charger that allows to fully recharge the vehicle in 4 hours.

3.3. Duty Cycle for Calendar Aging Experiments

The testing protocol for the calendar aging experiments is straight forward. The different cells will be stored unplugged in temperature regulated chambers at a set SOC.

Periodically the cells will be completely recharged and will be subjected to an RPT at room temperature. After the RPT is completed, the cell will be set back to the test SOC and placed back in the temperature chamber.

4. Experimental Approach

Design of experiment (DoE) strategies were examined in order to perform the optimum number of experiments and ensure that every experiment contributes to constructing a good understanding of both experimental plans (cycling and calendar aging). There are different types of DoE strategies [18] but they can mainly be divided into two categories, screening designs to obtain qualitative results and surface response designs to obtain quantitative results. Screening designs best fit when at least one of the factors (i.e. the different variables to consider) is non-continuous. They are therefore really adapted to our cycling study where we will alternate different unrelated duty cycles. Surface response designs offer the ability to quantify the relationship of several factors. They are therefore suited to the calendar aging study where we want to understand the combined effect of temperature and SOC on cell degradation on the entire experimental range.

4.1. Cycling Experiment

Experimental Cost. As discussed in the previous section, we want to investigate the effect of constant power V2G and G2V protocols on single cells. We also mention that the V2G and G2V protocols might have a combined effect with other variables such as the charging schedule, the charging habits (1 or 2 charges per day) and the charging level. It is therefore essential to study a matrix of tests encompassing the different combinations.

Summarizing the variables in our experiments, we have 4 parked steps and each step can be either a rest period, a V2G period or a charge period. Testing every combination separately would require 81 individual experiments which is unfeasible, so we therefore need to reduce the number of experiments. We accomplish this by setting a number of ground rules for the two consecutive parked steps (which makes a park period):

- The battery will not discharge or charge twice in a row.
- The battery will not discharge after being fully charged.

Based on these rules we can limit the number of combinations to 4 per parked period: Rest/Rest (R+R); V2G/Charge (V+C); Charge/Rest (C+R); and Rest/Charge (R+C) (Figure 5b). This will limit the number of combinations to 16. These 16 experiments can be arranged in a 4^2 fractional design, i.e. 2 factors (parked period 1 and parked period 2) and 4 combinations (R+R, V+C, C+R and R+C). The different combinations are summarized in Figure 5. The number of experiments can be further reduced to 15 by assuming at least 1 charge per day and thus eliminating the (R+R, R+R) experiment (dots on Figure 5a).

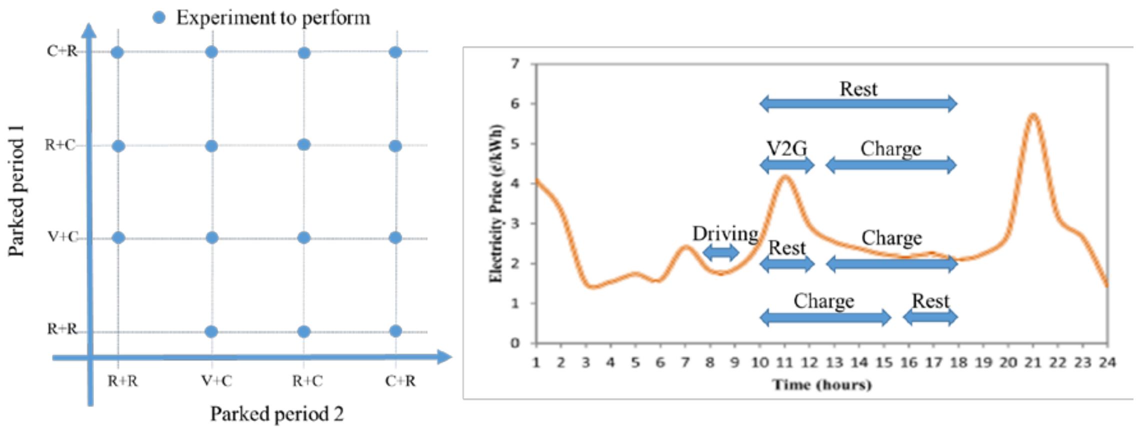

Figure 5: (a) Experiment matrix and (b) details.

This separation into 4 different combinations will allow us to determine the effect of V2G (V+C vs. R+C), the effect of G2V (C+R vs. R+C) and provide a baseline (R+R). Since the two parked periods have different charging characteristics (4 hours for period 1 and 8 hours for period 2) we can also address two more effects: 1 vs 2 charges per day and the effect of the charging power. Indeed, comparing the result of the (C+R,C+R) vs. (R+R,C+R) experiment will showcase the impact of 2 charges per day versus 1 charge per day. Moreover comparing the (R+R,C+R) to the(C+R,R+R) will showcase the impact of the charging level since the two parked periods have different charging characteristics (4h for period 1 and 8h for period 2).

The next issue to address is reproducibility. In order to have confidence in the observed effect, we want to repeat each experiment 3 times, increasing the number of experiments (experimental 'cost') from 15 to 45. Since our equipment has 40 channels in total; we will therefore divide the plan into at least 2 sets of experiments.

Figure 6 presents the different ways the experimental matrix could be split. The effect of V2G can be assessed in 12 experiments, adding 9 experiments allows addressing the effect of G2V and eventual combined effects with V2G. Adding 9 other experiments will allow addressing the effect of 1 vs. 2 charges a day and the combined effect with V2G and G2V. Finally, adding 9 last experiments will address the effect of charging power and all combined effects with V2G and G2V.

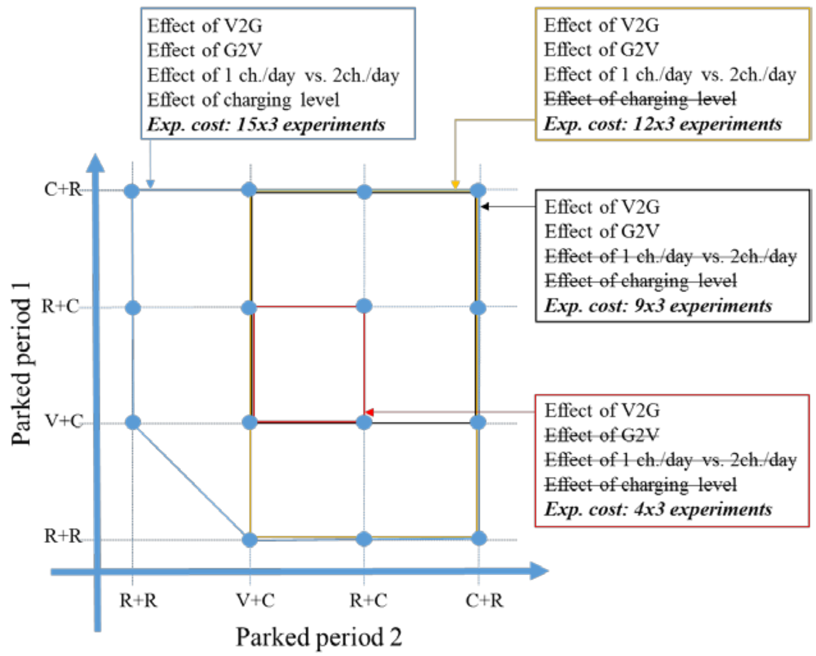

Figure 6: Plan splitting

Since the main topic of this work is to assess EV cell degradation under electric utility grid operations, we will first investigate the effect of V2G and G2V in this project. The splitting of the plan can then either be 27/21 leaving the effect of the charging for the second set of experiments or 36/9 and address the effect of 1 vs. 2 charges per day in the first year. We believe that splitting in 36/9 is the better option. It will give some increased flexibility by freeing some channels for the second stage of the experiment. It will also provide other EVTC team members maximum information on the potential drawbacks of V2G/G2V strategies more quickly. Because we will focus more on this experiment, we'll use the DoE approach to lighten the calendar aging study without sacrificing the end result of understanding the effect of SOC and temperature on the calendar cell degradation.

Test Acceleration. Ideally the tests should be performed at the same pace as real life to maximize the probability of having the same degradation. Unfortunately this is too time consuming and the test needs to be accelerated.

According to the defined protocols, the cells are to be in use for 15 hours every day (Figure 7). Therefore the maximum time that can be gained compare to real life is the remaining 9 hours. We believe that a little relaxation (30 min) is necessary because it will allow the cells to start the next cycle with a surface state closer to the real usage, thus mimicking more closely the real usage. The degradation associated with the 8 untested hours can be added later on when the effect of calendar aging is determined (cf. next section).

We therefore plan to test 24h of EV life in 16h, providing a 50% acceleration of the testing. This is accounting for the full charge time. The cells will never be completely discharged (at most 75%) thus the actual testing might be faster. However to insure consistency, it is recommended for every step to be the same length for every cell by adding relaxation time if needed.

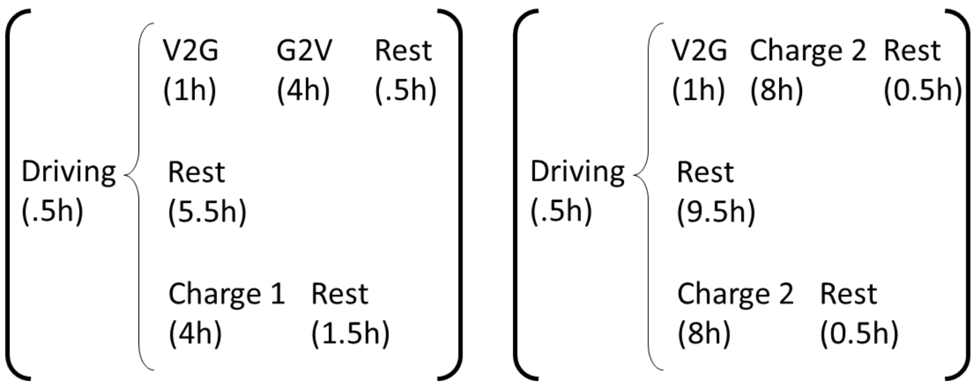

Figure 7: Test duration

A faster acceleration (100%) could be obtained by shortening the second charge to 4 hours. Unfortunately this will prevent us from comparing the effect of the 8 hour versus the 4 hour charge and any possible combined effects with V2G or G2V strategies.

4.2. Calendar Aging Experiment

Calendar aging consists in keeping cells unplugged at different temperatures for a set period of time, and conducting periodic reference performance tests to assess an eventual degradation. Calendar aging pace is known to be dependent on the cells SOC and on the environmental temperature. The SOC can be varied between 100% (fully charged) and 0% (fully discharged). For EV application, the temperature should be varied between -15°C and 55°C to encompass driving in different areas of the world.

We can reduce the number of experiments by using the DoE response surface methodology to optimize the different SOC and temperature combinations.

According to a classic response surface design strategy, the 'central composite' design of experiments [18], 9 tests are necessary to cover the entire range (Figure 8(a)). Unfortunately, this plan is not well adapted to our study because the literature survey performed in year 1 of this project showcased that calendar aging mostly occurs at temperatures above room temperature and at higher SOC, (Figure 8(b)). Therefore we will increase the density of experiments in the top-right quadrant, higher temperatures and SOC, to increase the accuracy of the resulting model. We will consider temperature as a discrete factor with 4 levels, -15°C, 25°C, 45°C and 55°C.

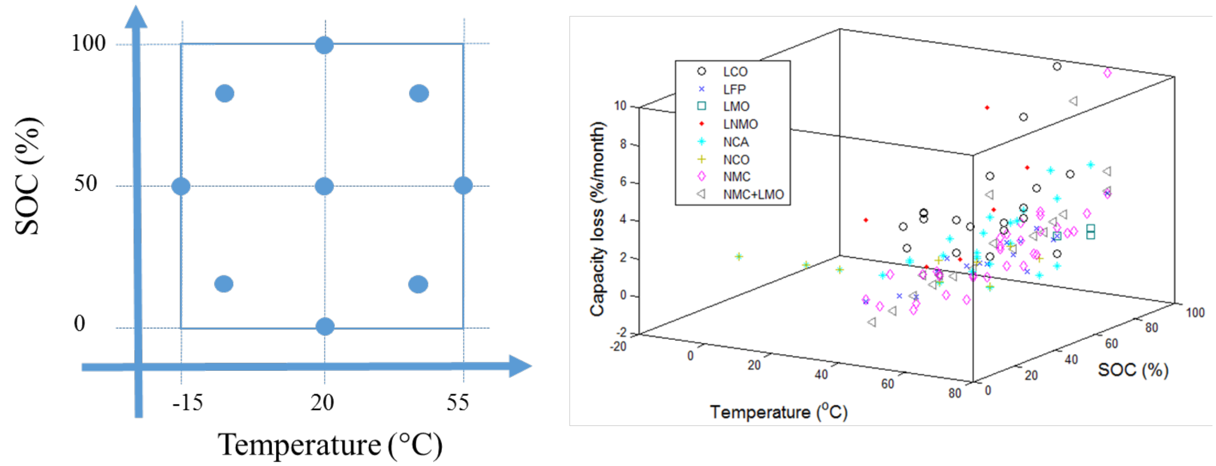

Figure 8: (a) Central composite design and (b) Effect of SOC and temperature on calendar aging from literature survey.

Based on the above constraints, a custom response surface plan can be designed by computer assisted methods [19]. An example of such a design is presented on Figure 9. The plan specifically chosen for this project has 8 experiments that will focus on high temperature and high SOC. 2 cells will be tested with each condition.

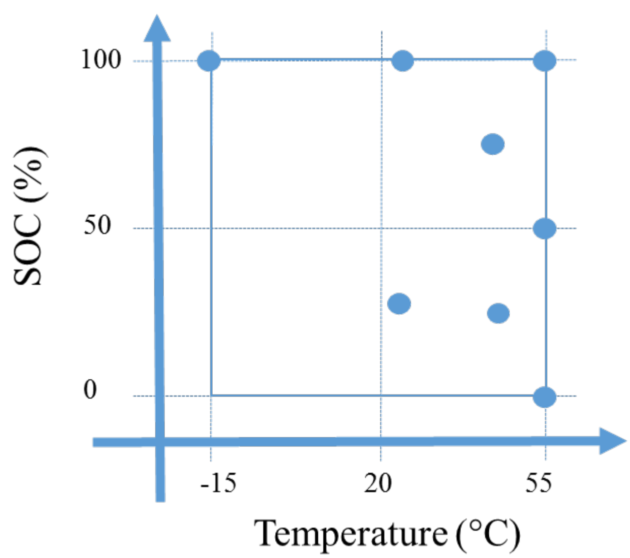

Figure 9: Example of an 8 experiment response surface design focused on high temperature & high SOCs.

5. Data Analysis

The experiments will compare 3 factors: capacity loss, power loss and degradation mechanisms. The degradation mechanisms will be inferred from the analysis of the changes in the cell's voltage response [20-22]. An analysis of the variance will also be undertaken to characterize the different effects. The complete analysis methodology will be described in a later report.

6. Cell Selection

Three battery chemistries seems to dominate the production for EVs today. One of them contains composite positive electrodes with a lithium nickel cobalt manganese oxide (NMC) and a lithium manganese oxide (LMO). This is believed to be used in, among others, the Volt. Another positive electrode, a nickel cobalt aluminum oxide (NCA), is believed to equip Tesla and Toyota cars. The Nissan Leaf uses a slightly different chemistry based on lithium nickel manganese oxide (LNMO).

Nissan Leaf LNMO cells as well as composite cells are not available commercially. (The composite cells are believed to be provided directly to Nissan by LG Chem.)
The NCA cells equipping the Tesla and Toyota are believed to be Panasonic 18650B cells, and are available commercially from a reputable US distributor (batteryspace.com [23]). We therefore selected those as the best cell candidate for this study.

7. Conclusions

Overall, the proposed project aims to test 54 battery cells in parallel for 23 individual experiments. The application of design of experiments techniques for both the cycling and the calendar aging study will allow us to derive the maximum amount of information in a timely manner. We will be able to access the impact of constant power V2G and G2V strategies as well as the impact of charging habits and levels. We will also be able to identify any combined effects within the different varied parameters.

8. Acknowledgements

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10. Appendix A: Formation and Reference Performance Test Detailed Protocols

Formation Test

Step 1
01 – Charge at current recommended by manufacturer until charge cutoff is reached,
02 – Hold charge cutoff voltage until a limiting current of C/25 is reached,
03 – Discharge at C/2 until discharge cutoff voltage is reached,
04 – Go to Step 1 twice.

If the discharge capacities of cycle 2 and 3 are within 0.2% go to step 2, otherwise repeat step 1.

Step 2
01 – Charge at Current recommended by manufacturer until Charge cutoff is reached,
02 – Rest 4h,
03 – Discharge at C/5 until discharge cutoff is reached,
04 – Rest 4h,
05 – Charge at Current recommended by manufacturer until Charge cutoff is reached,
06 – Rest 4h,
07 – Discharge at C/2 until discharge cutoff is reached,
08 – Rest 4h,
09 – Charge to 50% SOC for storage

Reference Performance Test
01 – Charge C/2 until Charge cutoff is reached,
02 – Charge at C/25 until Charge cutoff is reached,
03 – Rest 4h,
04 – Discharge at C/25 until discharge cutoff is reached,
05 – Rest 4h,
06 – Discharge at C/25 until discharge cutoff is reached,
07 – Rest 4h,
08 – Charge at C/25 until Charge cutoff is reached,
09 – Rest 4h,
10 – Charge at C/25 until Charge cutoff is reached,
11 – Rest 4h,
12 – Discharge at C/1 until discharge cutoff is reached,
13 – Rest 4h,
14 – Discharge at C/25 until discharge cutoff is reached,
15 – Rest 4h,
16 – Charge at C/1 until Charge cutoff is reached,
17 – Rest 4h,
18 – Charge at C/25 until Charge cutoff is reached,
19 – Rest 4h.