Mats K. Sundklakk

An investigation of lithium-ion battery degradation during shallow-, deep-, and combined cycles

Master's thesis in Energy Use and Energy Planning
Supervisor: Trond Leiv Toftevaag
June 2019

Master's thesis

NTNU
Norwegian University of Science and Technology
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Problem description

By continuing the work done in the project thesis last semester, this master thesis aims to execute enough cycle-tests on new lithium-ion batteries. By gathering the degradation data from the cycle-tests, this thesis tries to develop a hypothesis on a possible methodology to estimate battery life that are exposed to three different cycle-programs.

During the master thesis, the student shall:

- Do extensive literature search.
- Get experience using the Chroma 17020 Regenerative Battery Pack Test System
- Obtain enough battery degradation data.
- Develop a hypothesis for a possible methodology to estimate battery life that are exposed to three different cycle-programs.
- Write report.

The experiments are performed with the Chroma 17020 Regenerative Battery Pack Test System. The Battery Test System is owned by NTNU and is in the National Smart Grid Laboratory at Gløshaugen campus in Trondheim.

Abstract

This master thesis investigates the degradation rate of nine identical lithium-ion batteries. The batteries are the Super B 12V2600P-AC, which is a lithium iron phosphate-type ($LiFePO_4$). Every battery was new from the manufacturer. The experiments were conducted with Chroma 17020 Regenerative Battery Pack Test System situated in the National Smart Grid Laboratory in Trondheim, Norway.

Chapter 4 conducts a Performance and Capacity-test on all nine test objects. The test revealed the battery's actual capacity, voltage-profile, internal development of heat, and internal resistance. None of the batteries had experienced errors during production and performed as expected.

In chapter 5, the nine test objects were distributed across three different Cycle-tests and cycled as much as possible. The chapter describes the construction of the Cycle-tests and how the Battery Test System executed them. By cycling every battery almost 900 hours and 465 full cycles resulted in various levels of battery capacity fade and degradation. Other parameters, such as internal resistance, maximum temperature, and losses, are also presented in this chapter.

Sammendrag

Denne masteroppgaven undersøker degraderingsraten på ni identiske litium-ion-batterier. Batteriene er Super B 12V2600P-AC, som er en litium-jernfosfat-type (LiFePO4). Hvert batteri var nytt fra produsenten og hadde ingen tidligere brukshistorie. Forsøkene ble utført med Chroma 17020 Regenerative Battery Pack Test System som ligger i Det Nasjonale Smartgrid-Laboratoriet i Trondheim, Norge.

Kapittel 4 gjennomfører en Ytelse- og Kapasitetstest på ni testobjekter. Testen avslørte faktisk kapasitet, spenningsprofil, temperaturutvikling og indre resistans for alle batteriene. Ingen av batteriene hadde opplevd feil eller skade under produksjonen og presterte som forventet.

I kapittel 5 ble de ni testobjektene fordelt på tre forskjellige Sykel-tester og syklet så mye som mulig. Kapittelet beskriver konstruksjonen av Sykel-testene og hvordan batteritesteren utførte dem. Ved å sykle hvert batteri nesten 900 timer og 500 fulle sykler resulterte i ulike nivåer av degradering og kapasitet. Andre parametere, som intern resistans, maksimal temperatur og tap er også presentert dette kapittelet.

Preface

I chose this thesis due to its relevancy to battery technology. Battery technology, especially lithium-ion battery-technology, has in recent years become more relevant than ever. The number of applications that can be powered by battery technology keeps expanding every year. The challenges related to these applications are also growing. I have always had a fascination in observing how these challenges are solved. By choosing this project thesis, I would challenge myself in doing practical experiments, research, and documentation on battery technology, a field I have so much knowledge to pursue.

I want to thank Vladimir Klubicka and the rest of the service engineers at NTNU for helping me with the laboratory setup, access to essential equipment and continuous service.

I would also like to thank Dr. Olve Mo at SINTEF Energy Research. I highly appreciated your guidance and enthusiasm during this project.

Lastly, I would like to thank my supervisor, Trond Toftevaag, for always exhibiting patience, providing guidance, proposing creative and flexible solutions during this semester. During this project, I always felt my work was important, and that is mostly because of Trond.

Sincerely,

Mats K. Sundklakk

Mats K. Sundklakk
Student

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Chapter 1. Introduction

1.1 Background

Improvements in durability, power capability, cycle life, and energy density have made rechargeable batteries compatible as a power source in more and more applications. The most recent commercial use is electric vehicles and distributed power generation. During the next decade, it is likely that battery powered aviation- and marine transportation become commercial.

The load variation pattern used by battery manufacturers is often standardized and not like the actual load variation. As a consumer, it becomes challenging to estimate the battery's lifetime. This master thesis tries to increase the understanding of battery degradation by exposing equal batteries to different load variations. Figure 1.1 shows the new Battery Test System invested by NTNU and SINTEF Energy.

Figure 1.1: Chroma 17020 Regenerative Battery Pack Test System.

1.2 Objective

The objective of this master thesis is to gain a better understanding of battery life estimation by exposing equal batteries to different load variation patterns.

1.3 Scope of work

The work done in this report involves:

- Literature study
- Gain experience using the Battery Test System
- Create a recipe for an initial Performance and Capacity test
- Execute Performance and Capacity-test on all nine test objects
- Create three different Cycle-test-recipes
- Execute Cycle-tests
- Data management
- Documentation

1.4 Assumptions and limitations

It is assumed that the reader has a basic knowledge of battery technology. Some fundamental aspects of battery technology are not elaborated furtherly.

The main limitation of this project was time. The Cycle-testing and data management cost many hours. With more time, this thesis could produce more degradation data.

This report does not investigate the batteries self-discharge.

1.5 Software

This report utilized the software associated with the battery test system, Battery Pro, for creating recipes, executing tests, and extracting data. The data were managed and analyzed in Microsoft Excel 2016. The report was written in Microsoft Word 2016.

1.6 Report structure

Chapter 2 involves an elaborate study of lithium-ion history, principles, components and important terms and phenomenon in battery research.

Chapter 3 gives a walkthrough of every hardware module as well as every module in the software for the Battery Test System.

Chapter 4 introduces the first experiment in the report. Performance and Capacity-test of nine SB12V2600P-AC. The results include the battery's- capacity, voltage profile, heat development and internal resistance during several discharge rates.

Chapter 5 defines three different Cycle-tests to be run on the nine the batteries from chapter 4. This chapter also explains how to create the recipes for these tests. The results include the battery's- capacity fade, degradation, internal resistance, maximum temperature and energy losses.

Chapter 6 discusses the work done and findings in the results.

Chapter 7 is the thesis conclusion.

Chapter 8 elaborates on possible further work after this report.

Chapter 9 contains the bibliography with all references used in this report.

Lastly are the appendices. There are a total of seven appendices: A, B, C, D, E, F, and G. They contain information of the BTS, a summary of the BTS written by SINTEF Energy Research, module, specifications, various results, recipes and pictures.

Chapter 2. The lithium-ion battery

2.1 History

During the 1980s, portable computers, video cameras, mobile phones, and other portable electronic devices were developed, improved, and commercialized at a higher rate than ever. These improvements led to a growing need for rechargeable batteries with higher energy density, flexibility, and capacity. Conventional energy storage systems at the time were based on lead-acid, nickel, and nickel-cadmium. These batteries relied on liquid electrolytes, which made improving the energy density and size challenging. Because of this, research on an entirely new battery technology took place. [2]

By the beginning of the 1990s, the first generation of lithium-ion batteries became commercialized in a range of portable electronic systems. These batteries could utilize electrolytes made of polymers, which allowed designing smaller, lighter, and more flexible batteries with the same energy density and capacity. However, advantages came at the cost of reducing the ability to endure mechanical stress. [3]

Since the 1990s, other industries have seen the potential, done further research, and improvements to the technology. Today, lithium-ion batteries (LIBs) are dominating the energy storage market. Being used in almost every portable electronic device, electric vehicle, and energy production system. With further research and innovations, LIB-technology will keep improving the existing uses as well as new formats such as marine- and aviation vessels. [4]

2.2 Principle

A LIB is built up with one or more electrochemical cells. If more than one cell is used, they can be connected in series and parallel to each other to meet the voltage and current requirements. A battery cell contains the following key components:

- Positive and negative electrode
- Electrolyte
- Separator
- Enclosure

Key components and other components are illustrated in Figure 2.1.

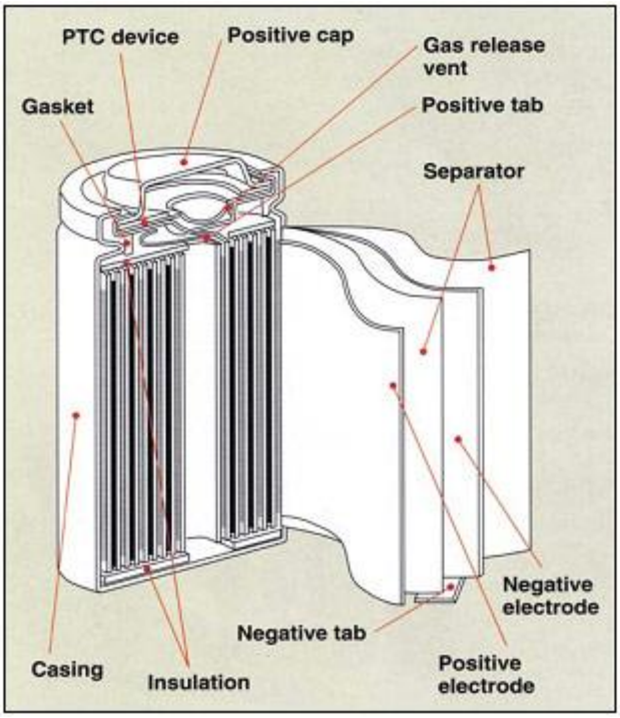

Figure 2.1: A LIB-cell with cylindric casing. [5]

2.2.1 Electrodes

The positive and negative electrode is often referred to as the cathode and anode, respectively. The cathode is the positive electrode when discharging and negative when charging.

Both electrodes are covered with electrode material coated on a metal foil that functions as a current collector. The cathode often consists of salts like lithium perchlorate ($LiClO_4$) or lithium tetrafluoroborate ($LiBF_4$) and the anode is often a graphite structure which has a low electric potential. The low electric potential makes the ions in the electrolyte react fast to the anode itself [4, 6]. Figure 2.2 illustrates the basic principle of LIBs.

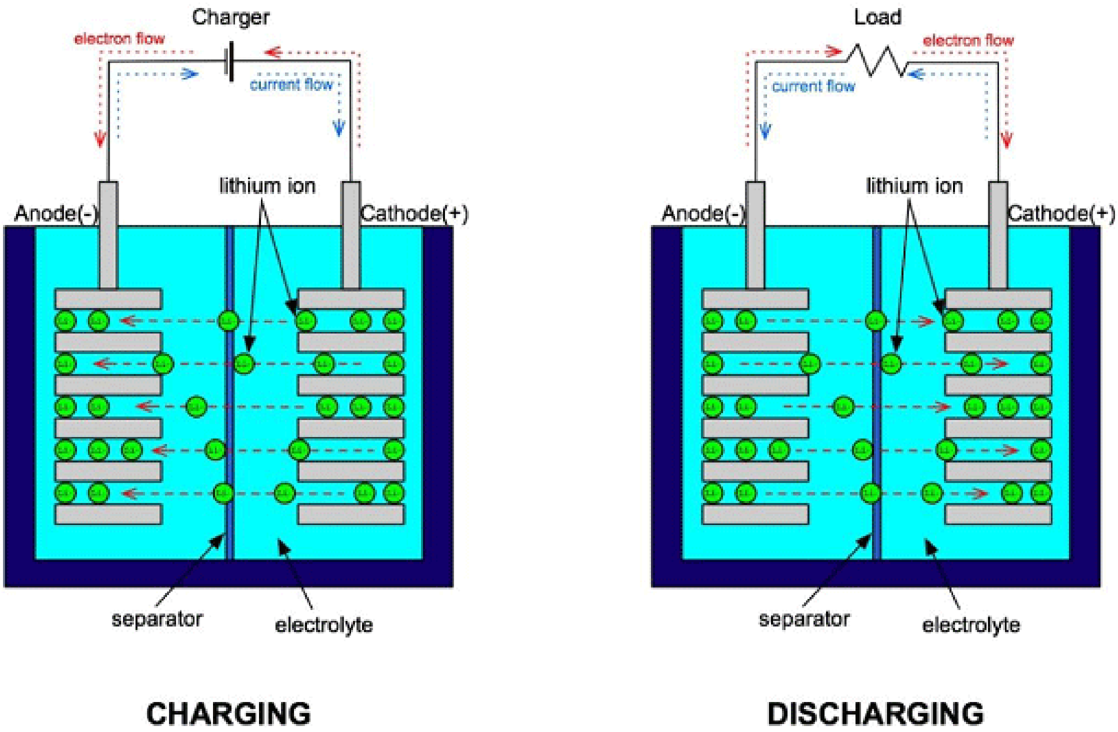

Figure 2.2: Basic working principle of a LIB in a charging- and discharging state. [7]

2.2.2 Electrolyte

The electrolyte in LIB cells is the matter that carries the lithium ions from one electrode, through the separator and to the other electrode. The electrolyte in LIBs is usually a liquid solution or a polymer. The liquid solution electrolyte usually contains organic solvents and dissolved lithium salt. Typical organic solvents are ethylene -, diethyl-, and dimethyl carbonate (EC, DEC, and DMC, respectively). The lithium salt is usually hexafluorophosphate ($LiPF_6$). The electrolyte solutions are highly flammable and pose a severe fire- and explosion hazard if cells are exposed to ventilation. The liquid electrolyte is not flooding the battery cell as in wet batteries. The active materials absorb it in the cell.

The other type of electrolyte is polymer. The polymer electrolyte has an excellent weight advantage over the liquid electrolyte. It is also more flexible and less flammable. However, the polymer has less ionic conductivity and is more susceptible to mechanic abuse. [4, 6]

2.2.3 Separator

The separator is the component that prevents the battery from short-circuiting. As the name would imply, the separator separates the electrodes electrically but allows lithium-ion particles to travel through. The separator is usually a thin polymer film, consisting of either polyethylene or polypropylene ($(C_2H_4)_n$ or $(C_3H_6)_n$, respectively). As Figure 2.3 shows, the separator in LIBs with polymer electrolytes can be stacked with the anode and cathode in layers to maximize space-efficiency.

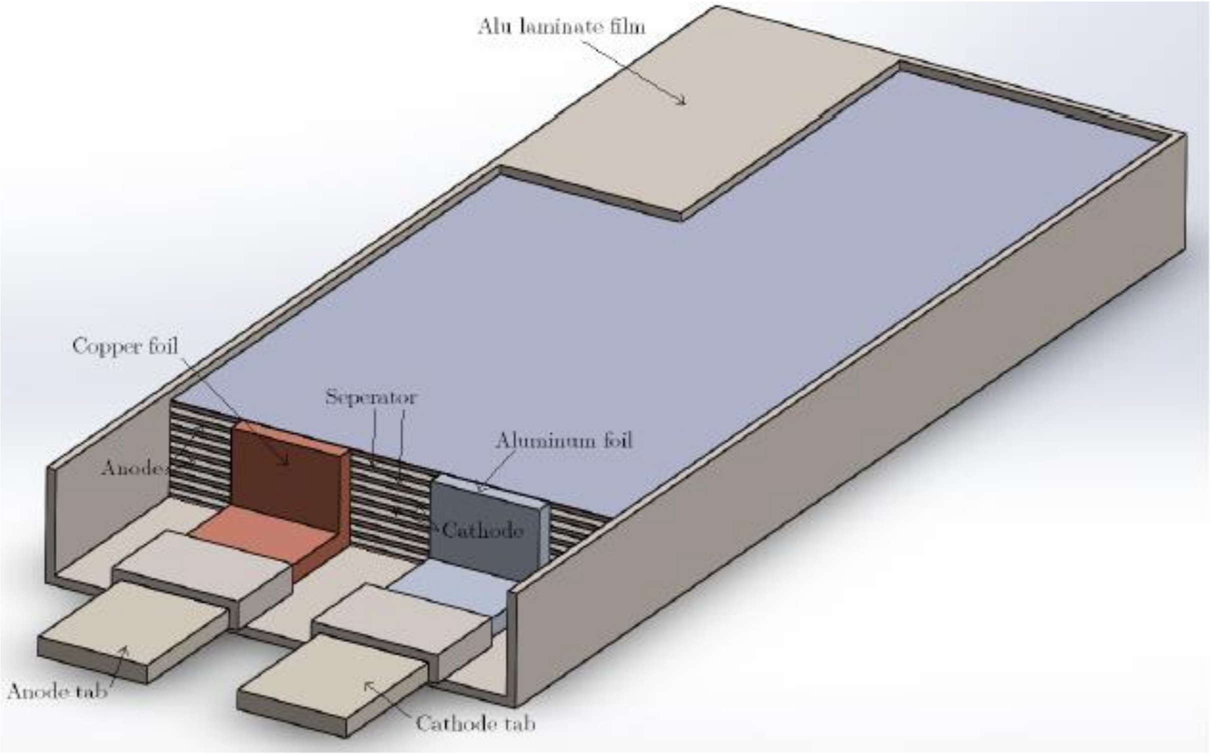

Figure 2.3: Illustration of a LIB-cell with prism casing and a polymer electrolyte. [3]

2.2.4 Enclosure

The enclosure of a LIB-cell is important to prevent electrolyte losses as well as contamination in the rest of the cell. The enclosure also protects the delicate parts of the cell as well as handling mechanical abuse.

2.3 Capacity, Coulombic efficiency, C-rating and Peukert's effect

2.3.1 Capacity

Electrical capacity is defined as the amount of current a battery can deliver over a period of time. Capacity is measured in ampere-hours, which is charge-based. Capacity can also be measured in Watt-hours, which is energy-based. Formula (2.1) and (2.2) describes two ways of defining electrical capacity. [8]

Actual capacity is the primary health indicator of a battery. When the actual capacity is compared to the rated capacity from the battery manufacturer, a reasonable estimate of the battery's health can be assumed. However, estimating the actual capacity in a battery can be a challenging task. The presumed best method of estimating actual capacity in a battery is the discharge method. The discharge method implies discharging the battery from a fully charged state, measuring the charge or energy. However, extensive battery testing shows that the discharge method is not always accurate, especially with lead-acid batteries. The same test procedures on the same battery often give different results for lead-acid batteries. This behaviour is not fully understood but may be caused by inconsistent chemical reactions in lead-acid batteries. Lithium-ion and nickel-based batteries perform far more consistent on capacity tests.[9, 10]

$$\boldsymbol{Q = I * t} \tag{2.1}$$

$$\boldsymbol{Q = \int_{t_0}^{t_1} I \, dt} \tag{2.2}$$

2.3.2 Coulombic efficiency

The coulombic efficiency, or faradaic efficiency describes how much charge the battery can deliver compared to what it can absorb. Formula (2.3) show the mathematical approach to coulombic efficiency. It describes coulombic efficiency as charge extracted from the battery over charge put into the battery over a full cycle.

The coulombic efficiency rating in LIBs is the highest in rechargeable batteries. It usually exceeds 99% depending on the charging rate and temperature. [11]

$$\boldsymbol{CE = \frac{Q_{out}}{Q_{in}} * 100\%} \tag{2.3}$$

2.3.3 C-rating

The C-rating of a specific battery delivers information of the current either delivered or received by a battery. 1 C is the amount of current required to discharge the battery fully within an hour. For example, 1 C for a battery with a 2.5 Ah capacity equals 2.5 A. 1 C for a battery with 10 Ah capacity equals 10 A. Formula (2.4) illustrates the current and rated charge relationship that makes the C-rating: [6]

$$\boldsymbol{C = \frac{I}{Q_{rated}}} \tag{2.4}$$

2.3.4 Peukert's effect

Peukert's law, developed by the German scientist Wilhelm Peukert in 1897 explains that the actual capacity in a battery depends on the discharge rate. With higher discharge, the actual capacity in the battery becomes less compared to a lower discharge. With lower discharge, the actual capacity becomes higher. Formula (2.5) explains the equation for Peukert's law. [12]

$$\boldsymbol{t = H * \left(\frac{C}{IH}\right)^{k}} \tag{2.5}$$

Where:

t: Actual discharge time [h]
H: Rated time with the actual discharge [h]
C: Rated capacity [Ah]
I: Actual discharge current [A]
k: Peukert's coefficient [#]

Peukert's law is limited. It does not consider battery temperature nor age. These factors have been proven to be very influential in battery performance. Peukert's coefficient is not equal for every battery. It is very dependent on battery type. A Peukert coefficient near the value of 1 indicates an ideal battery with no capacity loss. The higher the number, the less efficient the battery performs. Figure 2.4 illustrates the relationship between the discharge rate, available capacity, and Peukert's coefficient for a 120 Ah battery [13]. The illustration shows that higher Peukert's coefficient causes more capacity loss with higher discharge.

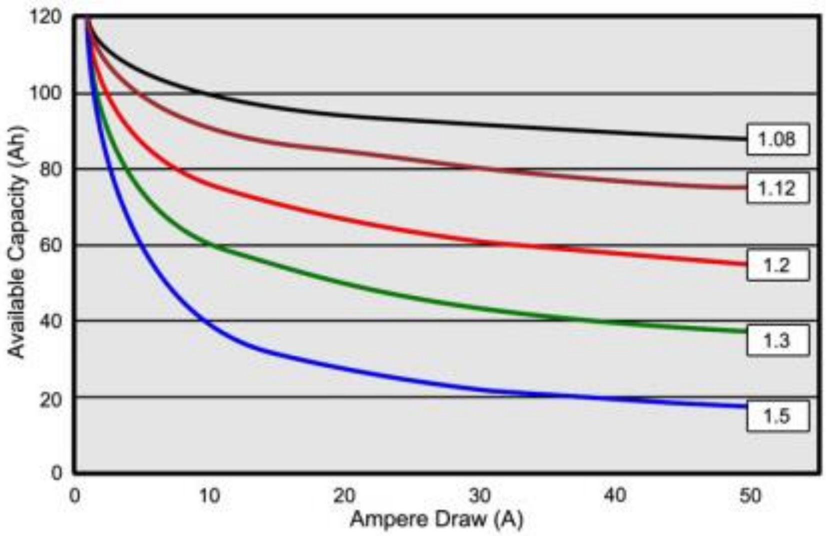

Figure 2.4: Available capacity versus Ampere drawn for a 120 Ah Battery. [13]

Peukert's effect is relatively much more present in lead-acid batteries than lithium-ion. Peukert's coefficient for LIBs are usually: $1 < k < 1.1$. [14]

2.4 State of Charge, State of Health and Saturated Charge

2.4.1 State of Charge

State of Charge (SOC) is the electrical equivalent to a fuel gauge in terms of providing feedback to the user how much charge remaining in a battery device. There are many reasons why SOC is essential. An obvious but straightforward example is the electric vehicle. Without continuous information of the SOC, there is no way knowing the driving range left in the vehicle. The SOC is also vital for the battery system as numerous battery parameters are strongly dependent, such as the voltage. It is essential to know that SOC does not indicate the available energy left in the battery. For instance, discharging a cell at constant current generates the most power in the beginning, due to the higher voltage level. Thus more energy is released in the beginning [15]. Figure 2.5 shows a typical relationship between voltage and SOC. Formula (2.6) describe the relationship between energy and voltage.

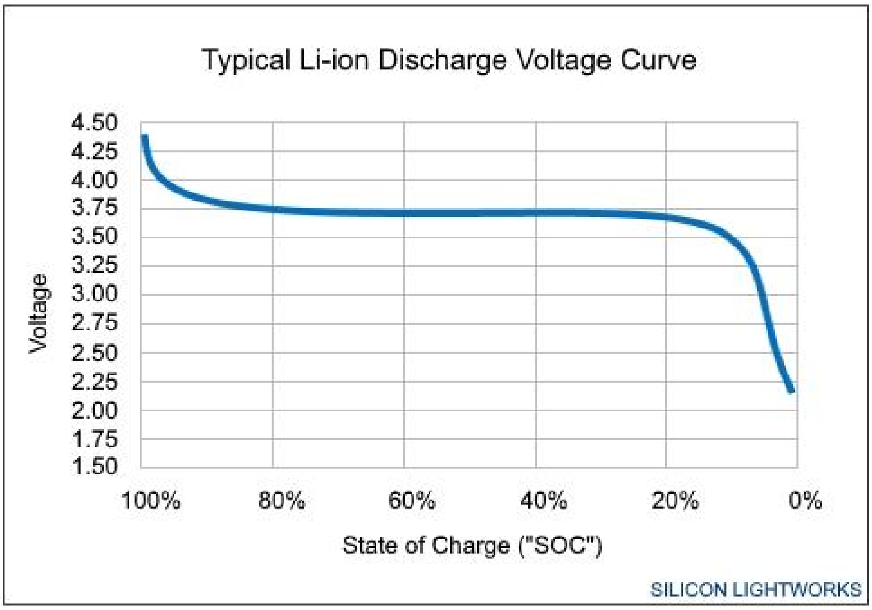

Figure 2.5: A typical voltage curve for a discharging lithium-ion cell. [16]

$$\boldsymbol{E = P * t = V * I * t} \tag{2.6}$$

There are many sophisticated ways of estimating SOC. Methods based on observational, mathematical, and chemical approaches. The chemical approaches are not addressed in this report. The most common ways of estimating SOC is:

- Coulomb Counting (observational)
- Open Circuit Voltage measurements (observational)
- Kalman Filtering (mathematical)

Coulomb counting is the most straightforward approach of the three. The rate of change in SOC is equal to the battery current divided by the battery capacity, see Formula (2.7). [15]

$$\frac{dSOC}{dt} = \frac{I}{Q} \tag{2.7}$$

Coulomb counting has several challenges. Firstly, to estimate SOC by current divided by charge, a correct starting point must be implemented. The starting point is usually at the end of the charge or end of discharge. [15]

Another limitation with coulomb counting is the accumulating rate of error. The longer the cycling continues, the more error accumulates. Utilizing precise current measurement tools can prevent major misreads. However, an error usually accumulates in some way or another. The maximum amount of error in current is εi. The maximum error in SOC is described in Formula (2.8). Figure 2.6 illustrates the error in SOC over time.

$$SOC_{error} = \frac{\varepsilon_i * t}{3\,600 * C} \tag{2.8}$$

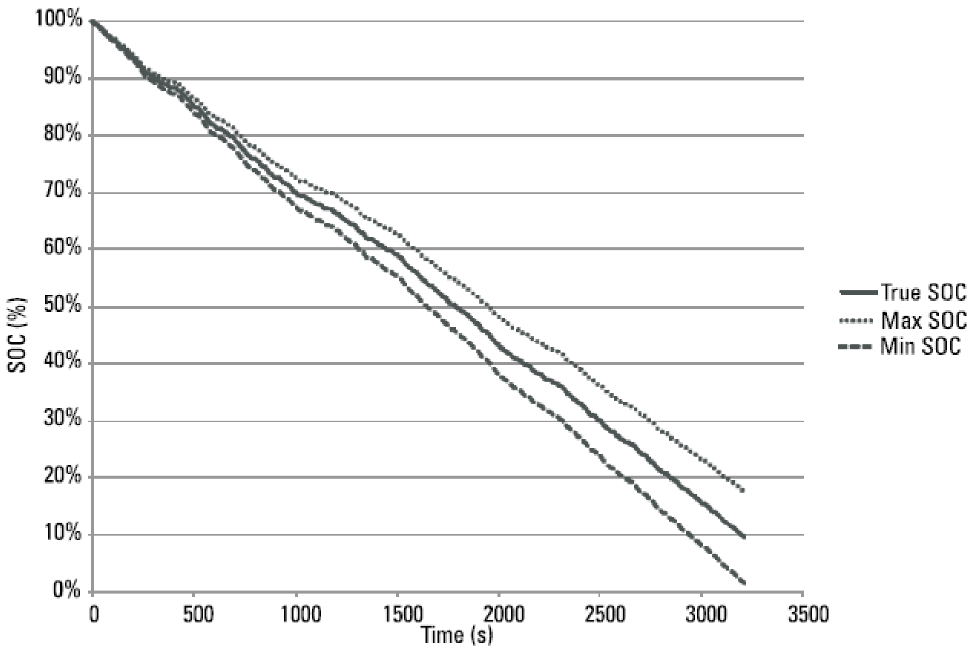

Figure 2.6: Accumulated error in SOC over time. [15]

Because of the accumulated error, the recommended action is recalibration. Recalibration is done by returning the battery to the end of- charge or discharge. [15]

If the SOC and the open circuit voltage (OCV) are dependent on each other, then the OCV can be used to estimate SOC. However, there are some limiting factors. For instance, it is necessary to account for cell hysteresis for OCV-measurement to be accurate. Another limiting factor, especially for lithium-ion batteries, is the relatively flat OCV-SOC-curve. A difference of 10-20 mV can represent a SOC-range of 30-60%. Lastly, the OCV should be completely relaxed before estimating SOC. Depending on the battery cell, this could take several hours or days to achieve. Figure 2.5 shows a OCV-SOC-curve. [15]

2.4.2 State of Health

State of Health (SOH) is an abstract concept that is used to set a numerical value to the health of a battery. It is used to indicate the level of battery degradation. SOH is usually represented with a percentage, where 100% is completely healthy and 0% is not operable at all. If this percentage declines below 80%, most actors in the industry defines the battery to have reached its end of life (EOL). The battery can still operate, but the battery has reached a point where it only can deliver a fraction of its rated capacity. Formula (2.9) shows the calculation of EOL. [17]

$$\boldsymbol{EOL\ is\ reached\ if}: \tag{2.9}$$

$$\boldsymbol{SOH \leq 80\% = \frac{Q_{actual}}{Q_{rated}} * 100\% \leq 80\%}$$

Estimating SOH is a complicated procedure. It is complex because of the number of variables involved. The most common way of describing SOH is looking at the *Capacity fade*. Capacity fade is the reduction of capacity in the battery. The reduction of capacity happens due to battery degradation, *Cycle life* as well as *Calendar life*. Cycle life is the number of cycles the battery has executed. Calendar life is the total time the battery has been operative. With increased cycle- and calendar life, the lithium-ions and electrons inside the cell have a harder time traveling from one electrode to the other. The lack of traveling particles contributes to restricting the battery in delivering its rated capacity. Other reasons to capacity fade can be mechanical damage. [17]

As the battery is aging, internal resistance increases. High internal resistance contributes to reducing capacity. Lithium-ion batteries with carbon-based anodes experience Solid-

Electrolyte Interphase (SEI) when activated for the first time. SEI-layer is a thin film of lithium-carbonate and lithium-oxide that increases with cycling. Eventually, the SEI-layer grows and creates an electrical barrier with the anode, lowering the capacity [17, 18]. The cathode can also develop a similar obstructing layer. This layer is called *Electrolyte oxidation* (EO). EO is caused by a voltage level above 4.10V per cell at high temperatures[19].

Another variable is the *Self-Discharge*. Self-discharge is the battery's ability to discharge itself. The rate of self-discharge increases with higher cycle- and calendar life.

SOH is conducted of three factors: [17]

- Capacity
- Internal resistance
- Self-discharge

2.4.3 Saturation charge

Saturation charge is to saturate every battery cell with charge. This is accomplished by decreasing the level of charge-current when the cell-voltage limit is reached. Figure 2.7 illustrates the relationship between charging current, cell voltage and charge capacity when saturation charging. [20]

Saturation charging can degrade the battery at a higher rate. Charging a battery to a lower voltage than the maximum voltage-level increases the longevity of the battery. Battery charger manufacturers tend to go for maximum capacity instead of maximum lifetime. Extended service life is perceived as less critical. [20]

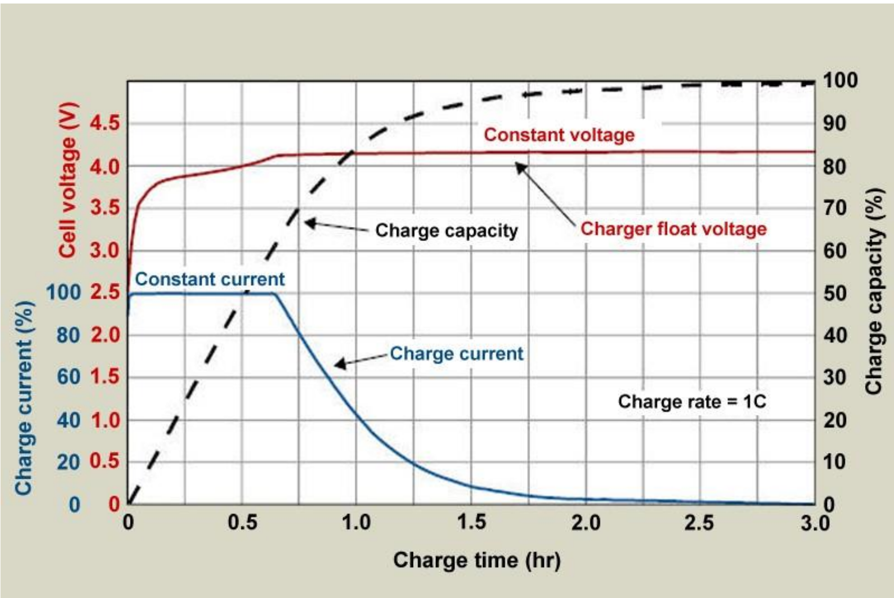

Figure 2.7: Relationship between charging current, cell voltage and charge capacity. [20]

2.5 Risk Assessment during battery testing

When performing experiments on batteries, there is always a risk of accidents involved. These risks need to be addressed and managed to minimize the chances of accidents and prevent injury and damage to the user and equipment.

2.5.1 Thermal runaway

When lithium-ion cells are discharging energy, heat generates. If the temperature of the cells exceeds a specific limit, the cells move into a state called thermal runaway. Thermal runaway keeps increasing the cell temperature until it either ignite or gets mechanically destroyed. Because of this, it is crucial to keep the cell temperature within the operating temperature range provided by the manufacturer. [6]

Most batteries have a venting mechanism that is designed to extract heat from the cells and transport it away. After the venting mechanism has transported the heat away, the battery is unable to be used again. Figure 2.8 shows a lithium-ion cell heated up to 220^{o}C before it explodes. [6]

2.5.2 Overcharge, Over- and undervoltage

Exceeding the upper voltage limit while charging causes the positive electrode in the cell to react with the electrolyte. This reaction creates heat, pressure, and flammable gases inside the cell. Should the temperature exceed a specific limit, the safety valve opens and releases the heat and flammable gases to the surroundings. However, this causes the surroundings to be temporarily flammable. [6]

Because of less stored energy, undervoltage is not as critical as overvoltage. However, undervoltage can cause the cell to short-circuit. [6]

Exceeding the recommended maximum charge-current level to a cell leads to a reduction of active lithium-ions in the electrolyte. This results in capacity reduction. The reduction of active lithium-ions due to overcharge is called *lithium plating*. Lithium plating creates a white powder that can short-circuit the cell. [6]

Figure 2.8: Heating of a SL-780 Li/$SOCl_2$ bobbin cell, resulting in an explosion at approximately 220°C. [6]

Chapter 3. Chroma 17020 Regenerative Battery Pack Test System

3.1 Hardware Components

The design of Chroma's 17020 model is for testing and measuring chargeable batteries, see Figure 3.1. It consists of three hardware components:

- DC/AC Bi-Direction Converter A691101
- Regenerative Charge/Discharge Tester 69225
- Charge/Discharge Controller 69200-1

Figure 3.1: Chroma 17020 Battery Pack Test System with one controller, one converter and two tester modules. [21]

Together these modules offer an efficient and practical way of measuring parameters during charge and discharge of a battery- module or pack. The application of the test system are many: [22]

- Drive cycle simulator
- Learning test for manufactory
- Life cycle test
- Balance control test
- Direct Current Internal Resistance test
- Capacity test
- Performance test
- Reliability test
- Overcharge/over discharge test

- Thermal test

17020 Battery Test System can be operated manually through the Charge/Discharge Controller 69200-1-module. However, it is recommended to use the related software, Battery Pro. Advanced test procedures can be programmed, ran, and observed in Battery Pro. The software also logs and presents the results in various formats such as PDF, CSV, and TXT. A summary of the battery test system given by SINTEF Energy is in Appendix B.

3.1.1 DC/AC Bi-Direction Converter A691101

The A691101 Bi-Direction converter is responsible for converting the AC-voltage from the grid to DC-voltage suitable for battery charging. Vica versa when discharging, the converter transforms DC-voltage into AC-voltage. Figure 3.2 shows the converter. Appendix C.1 shows the converter specifications [23].

Figure 3.2: Front panel of DC/AC Bi-Direction Converter A691101. [23]

3.1.2 Regenerative Charge/Discharge Tester 69225

The Regenerative Charge/Discharge Tester is responsible for the charging and discharging procedure when testing on batteries. The Tester can be operated both with the Controller-module or with Battery Pro. The Tester is illustrated in Figure 3.3. Figure 3.4 shows the operational range of the Tester. As Figure 3.4 illustrates, the Tester can operate in first- and second quadrant i.e., current can travel both directions.

The maximum current one Tester can deliver is 30 A. However, the Testers channels can be connected in parallel to achieve current up to 120 A. [24]

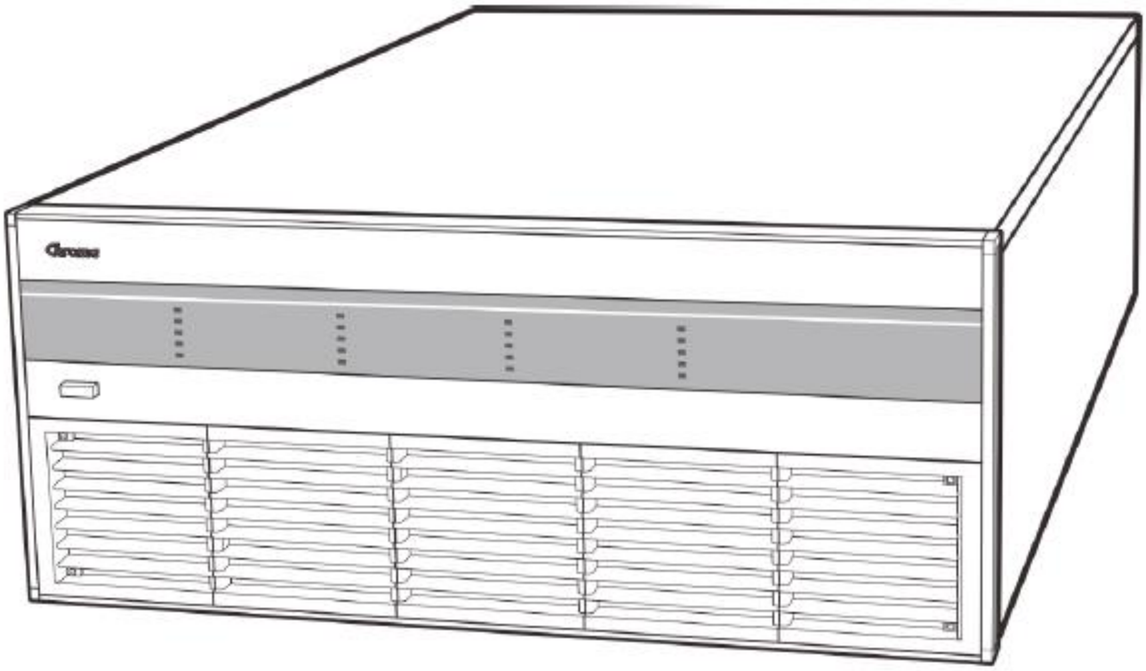

Figure 3.3: Front panel of Regenerative Charge/Discharge Tester 69225. [24]

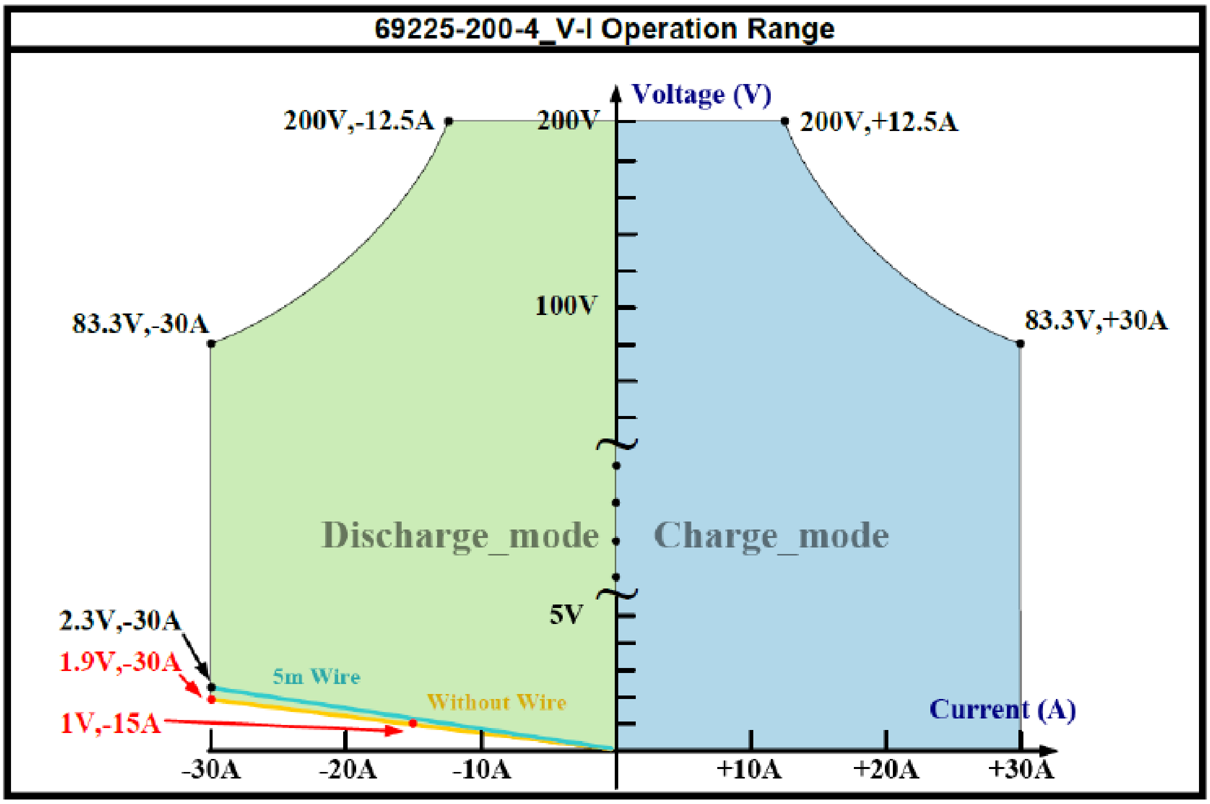

Figure 3.4: Operation range of Regenerative Charge/Discharge Tester 69225-200-4. [24]

3.1.3 Charge/Discharge Controller 69200-1

The Charge/Discharge Controller is the module that controls the operation of the testers. It can operate the Testers manually, or through Battery Pro. The controller receives data from the Testers at a sampling rate of 10 ms.

The front panel offers a display where various parameters from every channel show. The current, voltage, time, capacity, and power are some of the parameters displayed. Figure 3.5 show the front panel of the Controller-module.

Figure 3.5: Front panel of Charge/Discharge Controller 69200-1. [25]

3.2 Software: Battery Pro

Battery Pro is the associated software to the Battery Test System. Upon running Battery Pro, the opening window appears, see Figure 3.6. In the opening window, the different software modules are:

- H/W Configuration
- UUT Setup
- Recipe Editor
- Recipe Executor
- Report
- Management
- About

Figure 3.6: Battery Pro opening window.

3.2.1 H/W Configuration

In the Hardware Configuration module, the different hardware modules are configured to meet the test requirements. One can make a new hardware configuration or open an existing one. The hardware configuration module also offers the possibility to include and configure other components such as temperature sensors, chambers, battery management systems, and Testers. Figure 3.7 shows the configuration module under the hardware settings tab. [26]

By entering the Charging Port Setup tab, a new window opens. Under this tab, one can configure external components such as temperature meters and battery management systems. [26]

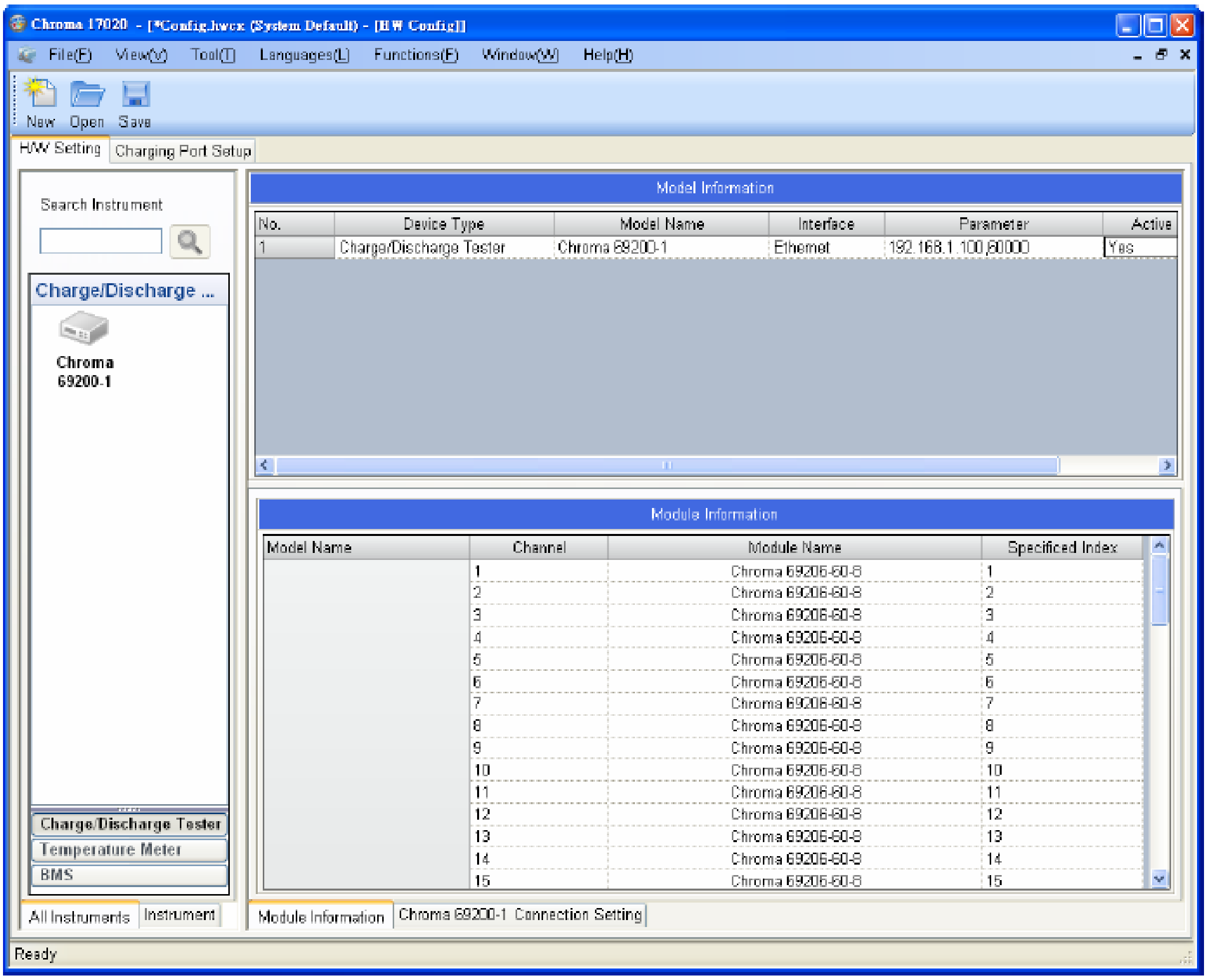

Figure 3.7: Hardware Setting. [26]

3.2.2 UUT Setup

In the *UUT Setup*, the user can create, edit, and save a Recipe Parameter-file that sets the allowable range for every parameter. The user can also choose default parameter values, which become the suggested value when creating recipes. The Parameter Recipe also sets limits for various protection schemes such as Over- and Under-Voltage Protection, Over Current Protection, and Over Temperature Protection. These protection schemes actively stops the test. Parameter Recipe can be saved and utilized in the Recipe Editor. Figure 3.8 shows the Recipe Parameter in UUT Setup. [26]

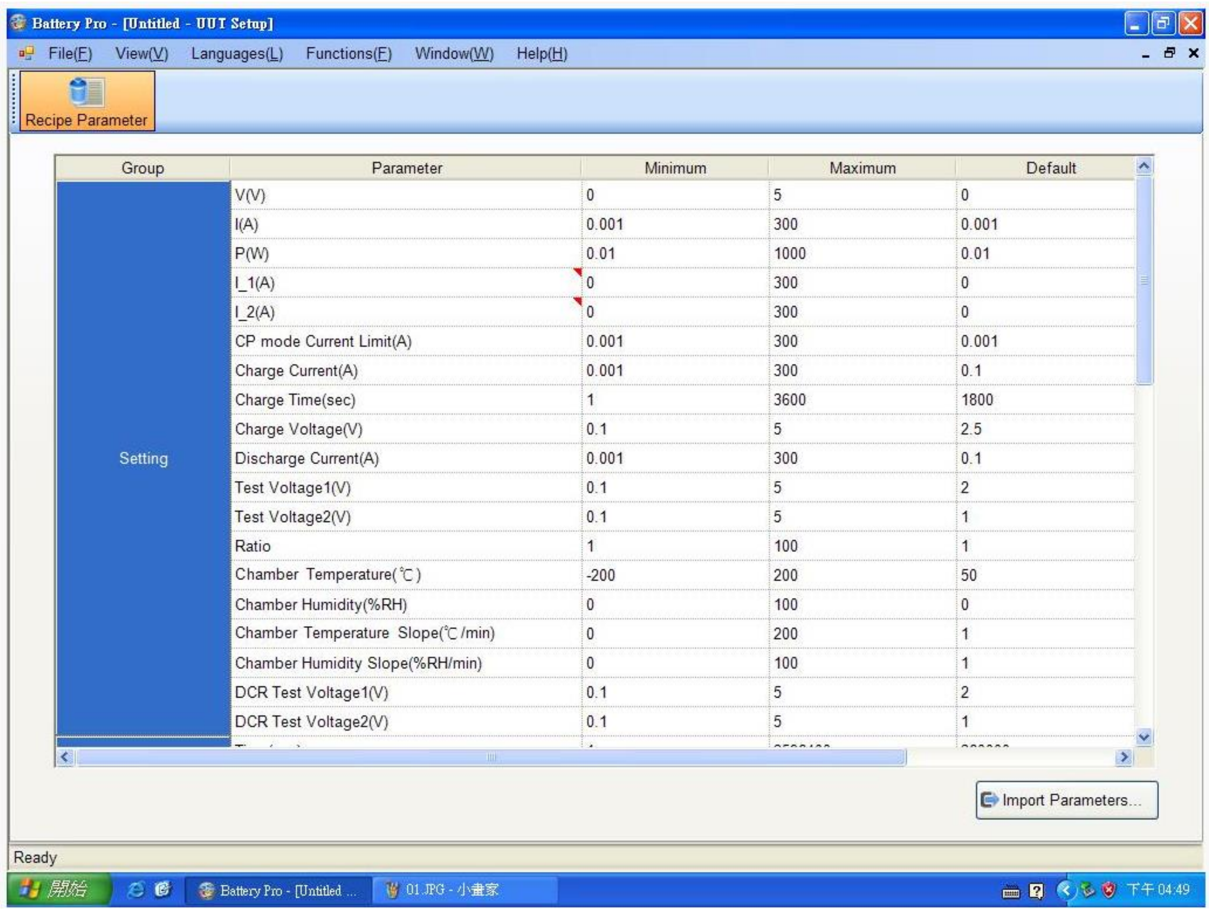

Figure 3.8: Setting allowable parameter range in Recipe Parameter, UUT Setup [27]

3.2.3 Recipe Editor

In the Recipe Editor module, the user can create a test recipe to execute on the battery. By applying step commands in the wanted procedure order, the test recipe executes them on the test objects once started. Each step, the user chooses to either charge or discharge the test object with constant current (CC), constant voltage (CV) or constant power (CP). After choosing a step, the step-settings and cut-off conditions are defined. After creating a test recipe, the recipe must be saved before used in the Recipe Executor. Figure 3.9 shows the Recipe Editor. [26]

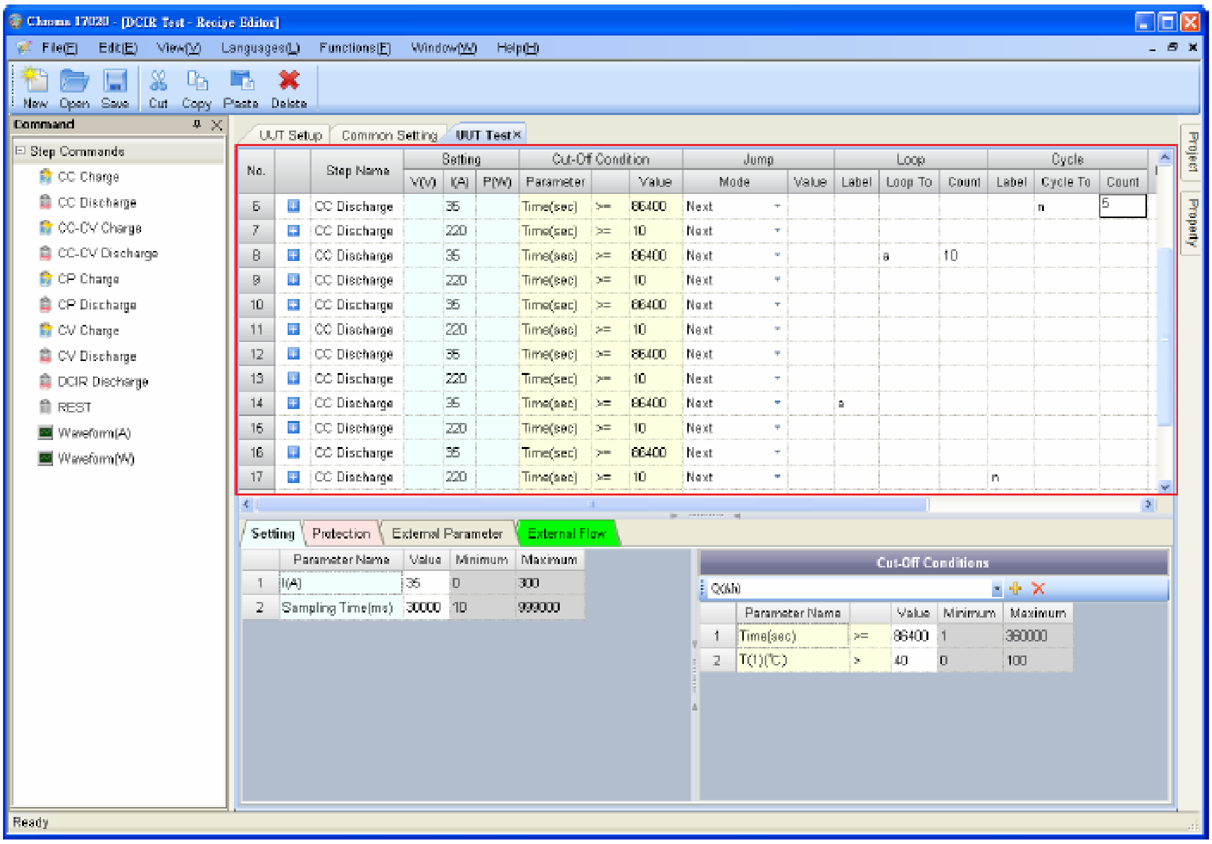

Figure 3.9: Recipe Editor, creating a recipe. [26].

3.2.4 Recipe Executor

Figure 3.10 shows the Recipe Executor in Battery Pro. In this module, the user can execute the recipes created in the Recipe Editor. The main window contains one battery monitoring display per channel. In Figure 3.10, there is a battery connected to channel 3, 4, 5, and 6. Each of the batteries is currently executing the Capacity Test. In the figure, the batteries are discharging.

Figure 3.10: Recipe Executor. [27]

3.2.5 Report

The last module in Battery Pro is the Report module. This module logs and stores parameter data from all tests executed. The Report module contains six different tabs:

- Report Generator
- Report Format
- Report Component
- Dump Data
- Data Analysis
- Merge.

Under the Report Generator tab, the user can choose to generate the report either in *SingleDetail*, which logs according to the sampling time, or *SingleStep*, which provides data from every step change.

The Report Component tab allows the user to choose which parameters to include from the data set.

In the Merge tab, the user can merge data from different test objects into a single file. For instance, in Figure 3.10, four test batteries are being run at the same time. Instead of generating one report at a time, the Merge trait can put all these data into one file.

Figure 3.11 show the Report module under the tab Report Generator.

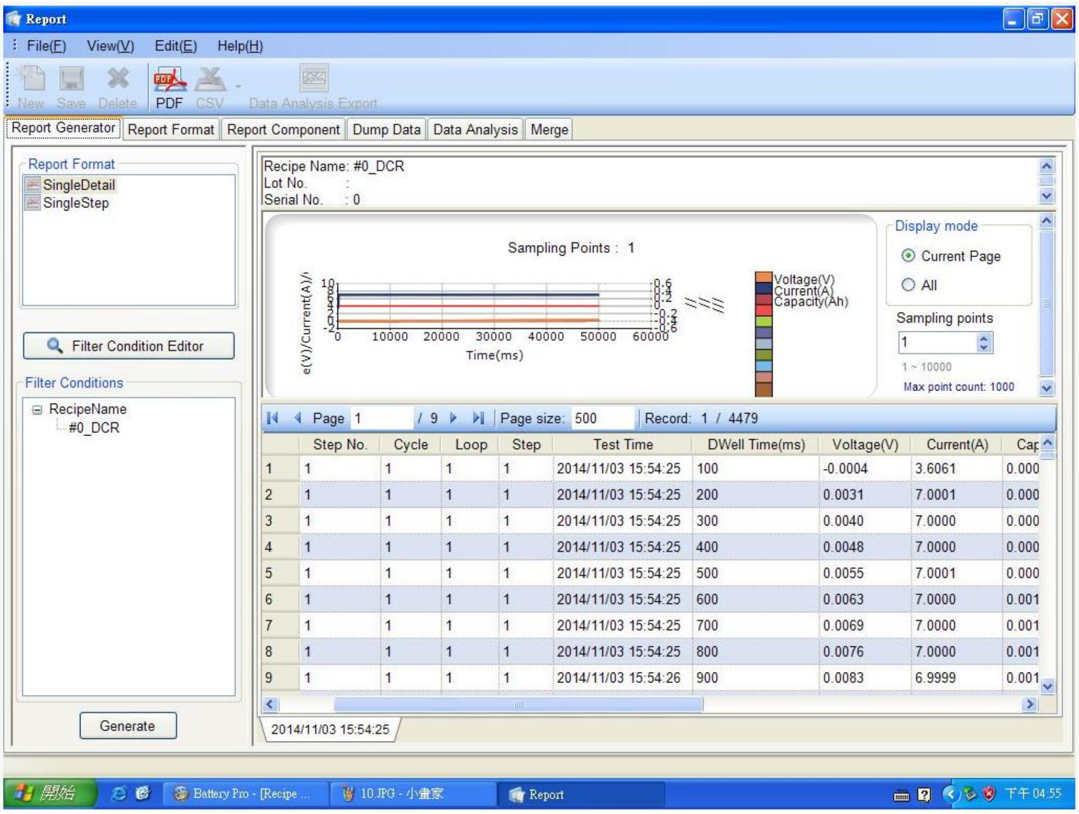

Figure 3.11: The Report-module under the Report Generator-tab. [27]

Chapter 4. Performance and Capacity-test

4.1 Introduction: Performance and Capacity-test

In this chapter, nine battery test objects perform a *Performance and Capacity-test* (PC-test). The PC-test is designed with *Chroma 17020 Regenerative Battery Pack Test System* (BTS). The battery test objects are the *Super B 12V2600P-AC*, see Figure 4.1. The essential specifications are in Table 4.1. A complete data-sheet of the Super B 12V2600P-AC is in Appendix C.3.

The batteries are entirely new and sent from the manufacturer. Thus, the actual battery capacity is expected to be the same as the rated capacity. The goal of the PC-test is to establish actual battery capacity, voltage profile, temperature development, and internal resistance of each test object.

This chapter also includes how to set up the laboratory components and provides a walkthrough of Battery Pro, the associated software to the BTS, on how to execute the PC-test.

Figure 4.1: Super B 12V2600P-AC [1].

Table 4.1: Super B 12V2600P-AC specifications [1].

Super B 12V2600P-AC	
Operating Voltage	13.2 V
Nominal Capacity	2.5 Ah
Charge Current	2.5 A
Charge Voltage Cut-off	14.6 V
Discharge Voltage Cut-off	8 V
High Operating Temp	+ 55 ^{o}C
Low Operating Temp	- 30 ^{o}C

The PC-test procedure steps are listed below. The PC-test is graphically illustrated in Figure 4.2. The batteries are put through Constant Current (CC) Discharge with discharge rate 1 C, 1.5 C, 2 C, 2.5 C and 3 C. With the specifications of Super B 12V2600P-AC, this is equivalent to 2.5 A, 3.75 A, 5 A, 6.25 A, and 7.5 A, respectively. The procedure steps are as follows:

1. Make sure the batteries are enough charged to perform a *Direct Current Internal Resistance-measurement* (DCIR-measurement).
2. Fully charge every battery by implementing *Saturation Charging*
3. Make the battery cells rest for two hours.
4. Execute CC Discharge.
5. Repeat step 2-4 with all discharge rates (1 C, 1.5 C, 2 C, 2.5 C, and 3 C).
6. Extract the data from Battery Pro.
7. Process and present the results.

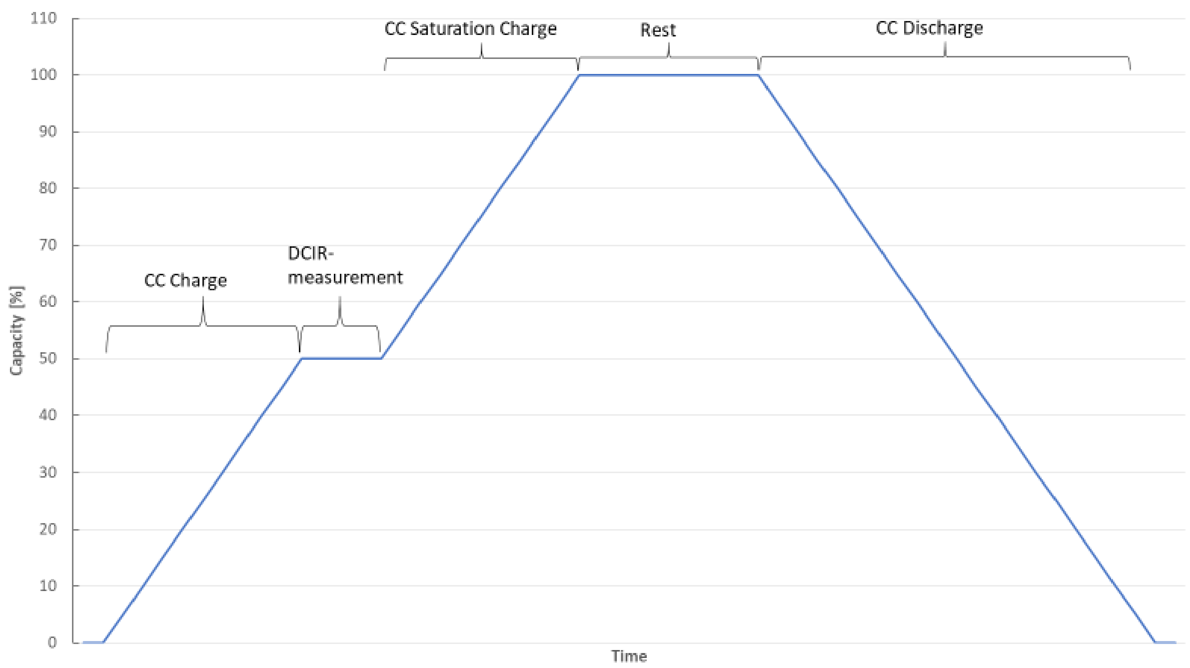

Figure 4.2: Performance and Capacity-test procedure. The figure only serves as a visual representation of the PC-test procedure.

4.2 Method: Performance and Capacity-test

This section explains how the laboratory components were set up. This section also elaborates on how to use Battery Pro to execute the PC-test.

4.2.1 Laboratory set-up

Table 4.2 shows which components were used to execute the PC-test.

Table 4.2: Components used in the PC-test.

Component	Type
Chroma Battery Test System (BTS)	AC/DC Bi-Directional Converter
	Regenerative Charge/Discharge Tester
	Charge/Discharge Controller
Lithium-ion battery	Super B 12V2600P-AC
Thermal sensor	Chroma
Climate chamber	ACS Discovery
Computer	w/ Battery Pro

A complete set-up scheme of the BTS is in Appendix A: Chroma Battery Test System.

From the BTS, cables are provided to connect to the test objects. Each Tester module has four channels. Each channel has cables to connect to the battery poles. Since the PC-test includes nine test objects, three Tester modules are required.

The batteries reside inside the ACS Discovery climate chamber. The climate chamber is set to maintain 25^{o}C. Appendix D.1 - Appendix D.4 shows the connection passage from the BTS to the test objects.

During the PC-test, the battery cells generate heat. Temperature sensors record the development of heat in the batteries. Unfortunately, only four sensors were available for the PC-test. These sensors were fastened to Battery 1, 2, 3, and 4, see Appendix D.5.

Figure 4.3 shows the laboratory workspace in its entirety.

Figure 4.3: Laboratory workspace.

4.2.2 Software set-up

Recipe Editor

In Battery Pro, the Recipe Editor is the module used to create the PC-test recipe. In the Recipe Editor, the preferred UUT-setup is chosen. An UUT-setup designed after the test object specifications is recommended when creating the PC-test.

To create the PC-test recipe, the cut-off conditions for each step must be identified. The cut-off conditions for the PC-test are:

- Minimum- and maximum battery voltage during saturation charge and full discharge
- Approximately 50% charge to perform DCIR-measurements
- Resting time.

The voltage levels are obtained from the battery specifications in Appendix C.3.

Fifty percent of the battery’s rated capacity equals 15.89 Wh.

Table 4.3 shows the cut-off conditions for the PC-test. Table 4.4 illustrates every measure used in the PC-test recipe. Appendix F.1 shows the recipe in the Recipe Editor. The recipe is based on the PC-test procedure in Figure 4.2.

Table 4.3: Cut-off conditions required for the PC-test.

Cut-off conditions:	
V_{max} [V]	14.6
V_{min} [V]	8
$E_{50\%}$ [Wh]	15.89
Rest [s]	7 200

Table 4.4: A complete overview of the PC-test recipe.

Step No	Step Name	I(A)	Cut-off Condition	Loop label	Loop to	Count	Cycle label	Cycle to	Count	Description
1	CC Discharge	2.5	Time >= 7200							Make sure the battery is completely discharged
2	CC Charge	2.5	Wh > 15.89							Charge up to approximately 50%
3	DCIR Discharge		T1 > 20 T2 > 20							DCIR Discharge
4	DCIR Charge		T1 > 20 T2 > 20							DCIR Charge
5	CC Charge	2.5	V > 14.6							Saturation Charge (1 C)
6	CC Charge	1.25	V > 14.6							Saturation Charge (0.5 C)
7	CC Charge	0.6	V > 14.6							Saturation Charge (0.24 C)
8	CC Charge	0.3	V > 14.6							Saturation Charge (0.12 C)
9	CC Charge	0.125	V > 14.6							Saturation Charge (0.05 C)
10	Rest		Time >= 7200							Rest for two hours
11	CC Discharge	2.5	V < 8							Complete Discharge with 1 C
*	…	…	…							…
39	CC Discharge	7.5	V < 8							Complete Discharge with 3 C

*: Step 5 – 11 are repeated with a discharge rate of 1.5 C, 2 C, 2.5 C, and 3 C.

Recipe Executor

The PC-test recipe is applied to every test object in the Recipe Executor. Once applied, Performance and Capacity-test can start.

Report

When the test program finishes, the report module extracts data from the test. In this report, the data is obtained from the merge-tab as a csv-file and used in Microsoft Excel for data management and analysis.

4.2.3 Risk Assessment Measures

Safety measures are utilized to prevent accidents. The BTS is equipped with several protection schemes, such as; Over Temperature Protection (OTP), Overcurrent Protection (OCP), Over Voltage Protection (OVP), Under Voltage Protection (UVP), and more.

Another safety measure is the ACS Discovery climate chamber, which acts as a physical barrier between test objects and other equipment.

Lastly, the energy storage laboratory has proper ventilation, fire extinguisher, defibrillator, and power emergency stop.

4.3 Results: Performance and Capacity-test

This section presents and explains the results obtained from the Performance and Capacity-test.

4.3.1 Battery capacity

Table 4.5 show the battery capacities measured at 1 C discharge rate. Figure 4.4 and Figure 4.5 illustrate the best- and worst battery capacities in both Watt-hours (Wh) and Ampere-hours (Ah) at different discharge rates. The other batteries capacities are in Appendix E.1 and Appendix E.2.

Table 4.5: Actual battery capacity in Wh and Ah measured at 1 C discharge rate.

Battery	Rated Capacity [Wh]	Actual Capacity [Wh]	Actual Capacity [$\%_{Wh}$]	Rated Capacity [Ah]	Actual Capacity [Ah]	Actual Capacity [$\%_{Ah}$]
1	31.775	31.42	98.88	2.5	2.49	99.6
2	31.775	31.38	98.76	2.5	2.49	99.6
3	31.775	31.46	99.01	2.5	2.5	100
4	31.775	31.43	98.91	2.5	2.49	99.6
5	31.775	31.47	99.04	2.5	2.5	100
6	31.775	31.19	98.16	2.5	2.48	99.2
7	31.775	31.41	98.85	2.5	2.49	99.6
8	31.775	31.51	99.17	2.5	2.49	99.6
9	31.775	31.50	99.13	2.5	2.5	100

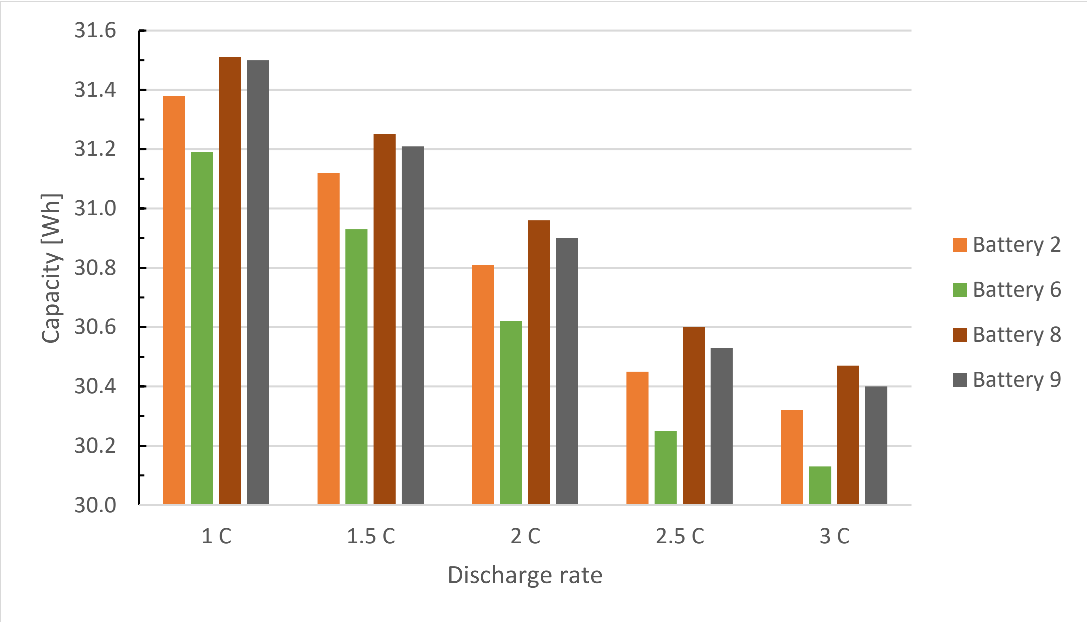

Figure 4.4: The batteries with most capacity (Battery 8 and 9) and least capacity (Battery 2 and 6) during the PC-test. Capacity measured in Wh.

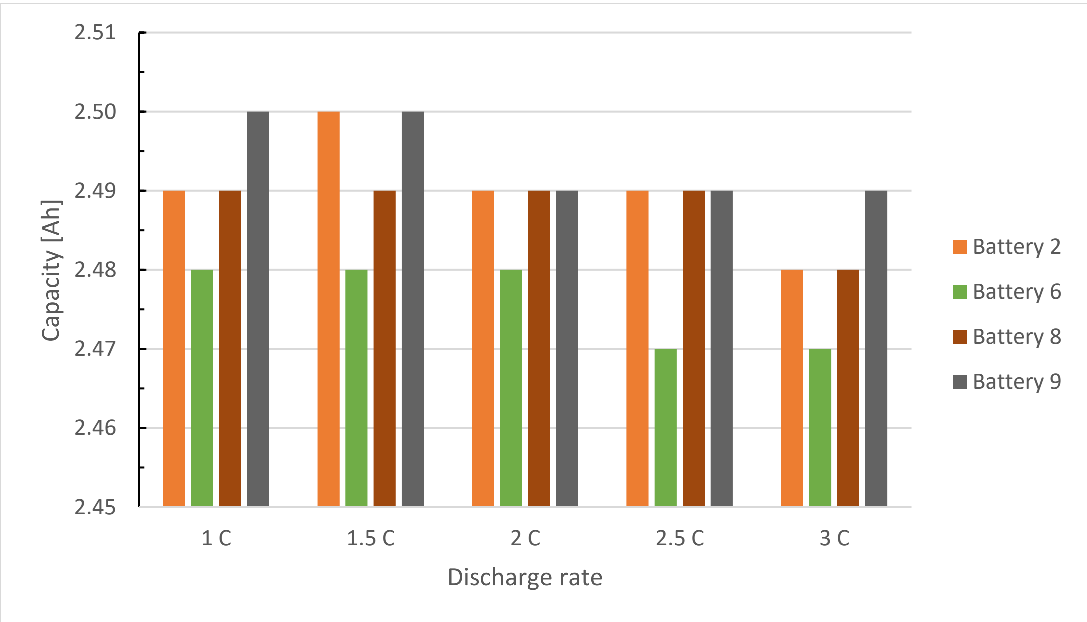

Figure 4.5: The batteries with most capacity (Battery 8 and 9) and least capacity (Battery 2 and 6) during the PC-test. Capacity measured in Ah.

4.3.2 Voltage profiles

Figure 4.6 shows the voltage profile for every battery at 1 C discharge. Every voltage profile is almost equal, which is expected of new batteries. Figure 4.7 illustrates the voltage profile of Battery 1 at multiple discharge rates. The voltage profile of Battery 2 - 9 at multiple discharge rates are in Appendix E.3 - Appendix E.10.

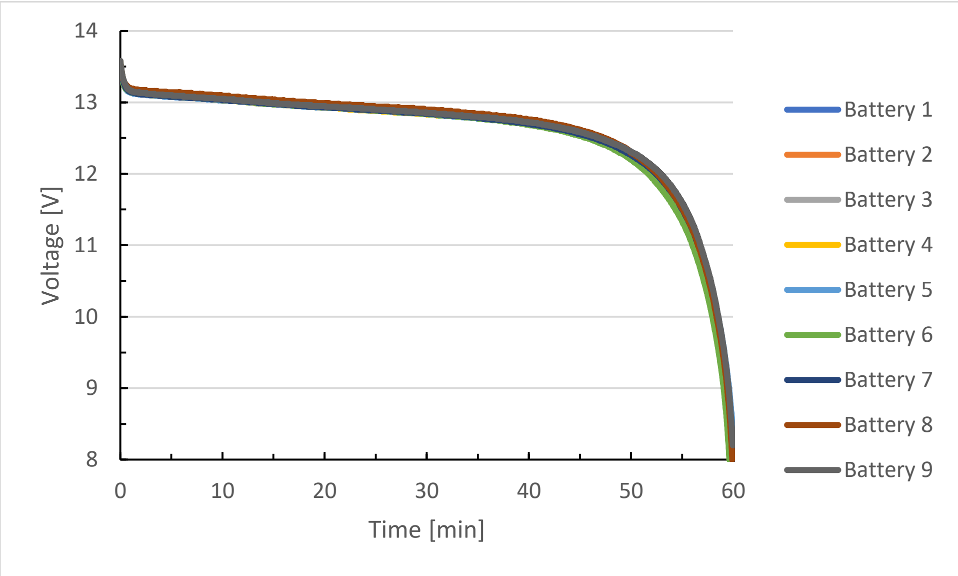

Figure 4.6: Voltage profile for every battery at 1 C.

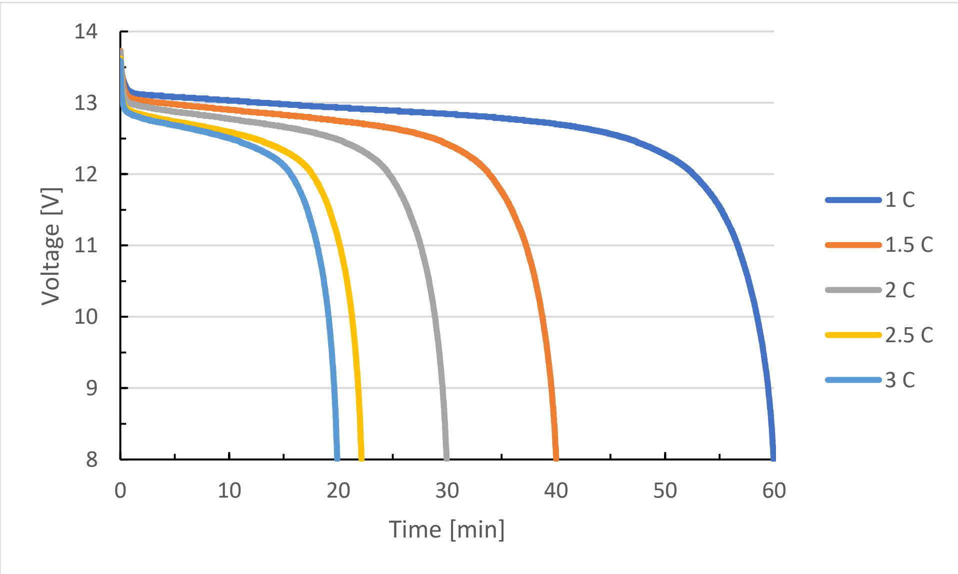

Figure 4.7: Voltage profiles for Battery 1 at several discharge rates.

4.3.3 Direct Current Internal Resistance measurement

Table 4.6 display batteries internal resistance measured during charge and discharge with the DCIR-steps. Figure 4.8 illustrates every battery's internal resistance during discharge. The battery's internal resistance during charge is shown in Appendix E.11**.**

Table 4.6: Every battery's measured internal resistance during charge and discharge.

Internal Resistance [mΩ]		
Battery	**Charge**	**Discharge**
1	22.17	24.41
2	26.52	26.91
3	22.47	21.69
4	24.99	24.07
5	26.71	26.26
6	25.39	24.89
7	24.15	25.86
8	12.06	10.69
9	22.15	22.54

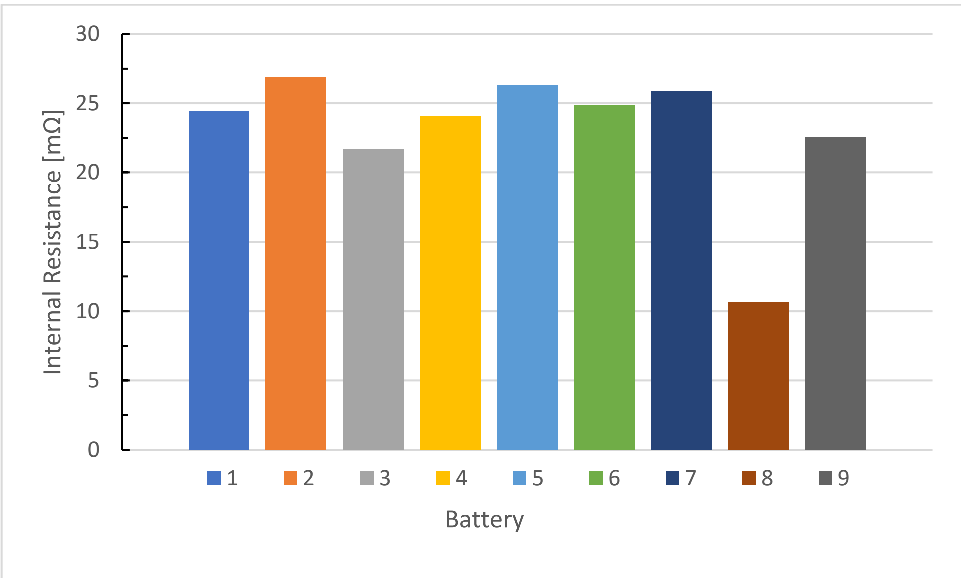

Figure 4.8: Every battery's internal resistance during discharge.

4.3.4 Heat generation

Figure 4.9 shows the temperature development in the four batteries that had a temperature sensor attached. Figure 4.10 illustrates the temperature development in Battery 1 at different discharge rates. Battery 2, 3, and 4's temperature development with different discharge rates are in Appendix E.12 - Appendix E.14.

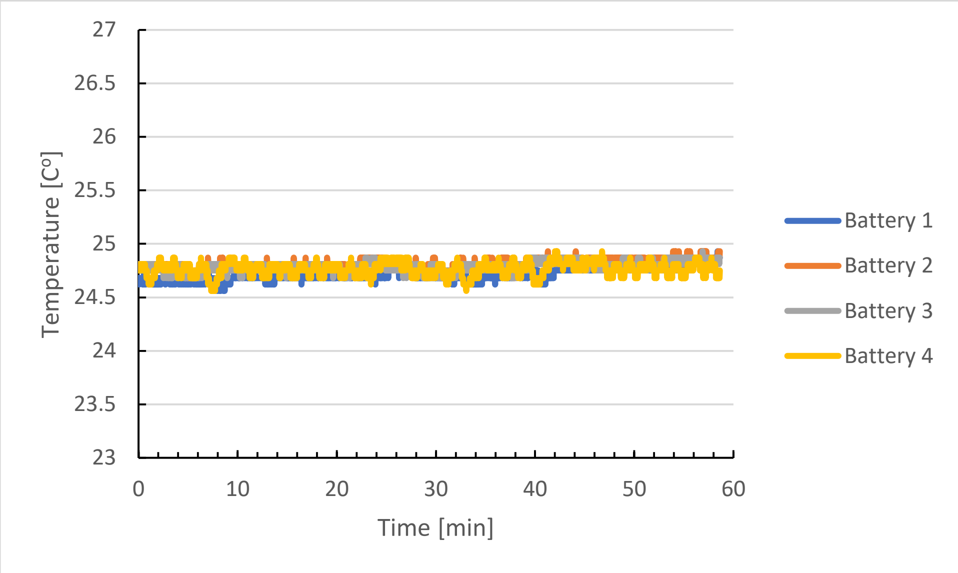

Figure 4.9: Temperature development in Battery 1 - 4 at 1 C.

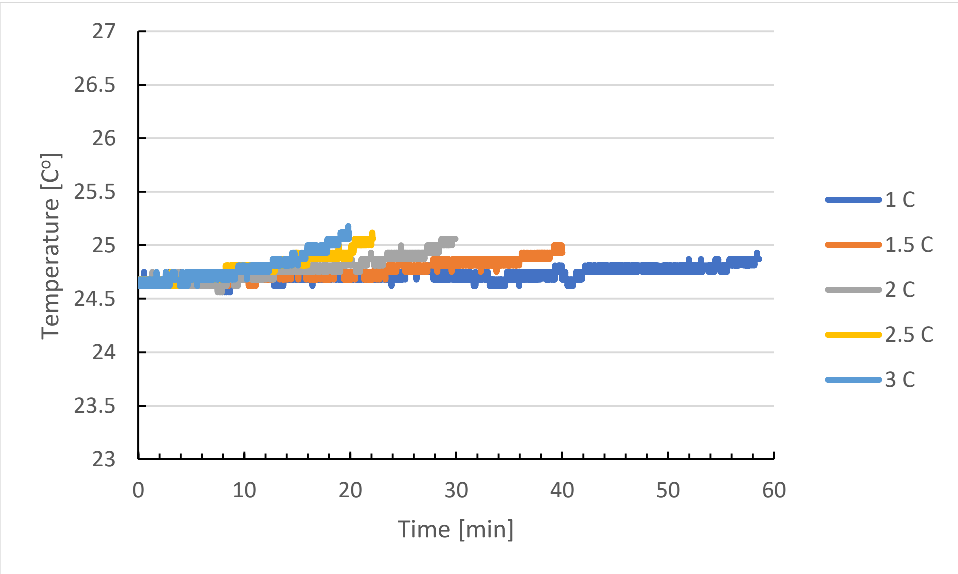

Figure 4.10: Temperature development for Battery 1 at multiple discharge rates.

4.4 Observations: Performance and Capacity-test

The Performance and Capacity-test were done without temperature sensors on Battery 5 - 9.

According to Table 4.5, there are differences between the actual capacity- in Watt-hours and Ampere-hours. Especially with higher discharge rates (Figure 4.4 versus Figure 4.5, and Appendix E.1 versus Appendix E.2). Watt-hours are the preferred unit for capacity in the next chapters.

Every test object has a similar voltage curve at 1 C discharge. According to Figure 4.7 (and Appendix E.3 - Appendix E.10), there is a decline in operative voltage at higher discharge rates.

The batteries have similar internal resistances, except Battery 8. Battery 8's internal resistance is about half of the other batteries.

Battery 1 – 4 develops little heat. The battery temperature does not surpass 25 ^{o}C at 1 C discharge rate for any of the four batteries. Battery 4 has a similar temperature development for all discharge rates.

Chapter 5. Cycle-tests

5.1 Introduction: Cycle-tests

In this chapter, nine SB12V2600P-AC batteries from the PC-test performs three different Cycle-tests. There are three batteries assigned to each Cycle-test. The Cycle-tests are:

- *Shallow Cycle-test*
- *Deep Cycle-test*
- *Combined Cycle-test*

Dr. Olve Mo (SINTEF Energy) developed the Cycle-test procedures with the help of Prof. Trond Toftevaag (NTNU). Instead of cycling around 50% capacity, the Cycle-tests cycles around 60% capacity to make the Cycle-tests more realistic.

The batteries executes as many Cycle-test runs as possible to achieve the most amount of degradation. Other results presented are maximum temperature, internal resistance, and losses.

The Cycle-tests are constructed, performed, and analyzed using the Chroma 17020 Regenerative Battery Pack Test System and Battery Pro.

5.1.1 Shallow Cycle-procedure

The Shallow Cycle-procedure contains a series of shallow cycles. In this report, the shallow cycles cycle between 65% - 55% of the batteries rated capacity. A relatively low depth of discharge should result in a relatively low degradation rate [28]. The data obtained from the Shallow Cycle-test serves as reference-data to be compared with the results from the other two Cycle-tests. Battery 1, 5, and 7 from the PC-test run the Shallow Cycle-test.

Figure 5.1 shows the Shallow Cycle-procedure. The figure illustrates 20 shallow cycles, which is not representative of the actual Shallow Cycle-test. The actual test performs 400 shallow cycles before running a capacity check. A long cycling part is to ensure that the battery degradation is mainly because of cycling, not the capacity-check.

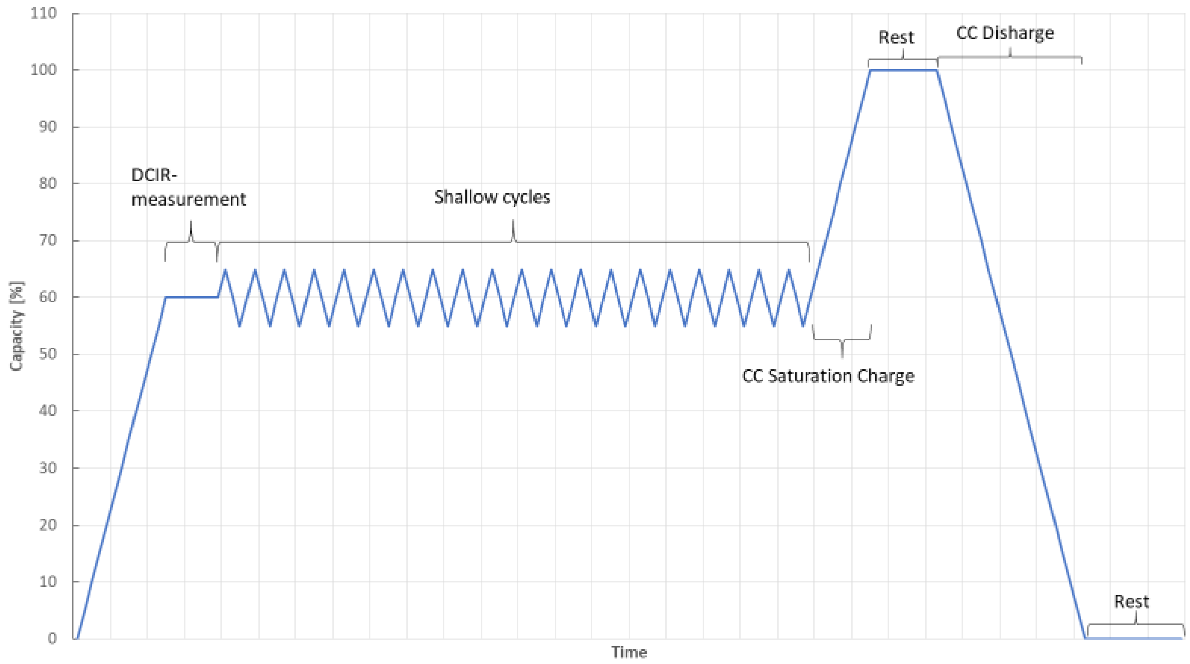

Figure 5.1: Shallow Cycle-procedure. There are only 20 shallow cycles shown in the illustration, while the actual test performs 400 shallow cycles. The Shallow Cycle-recipe is based on this illustration.

5.1.2 Deep Cycle-procedure

The Deep Cycle-procedure is similar to the Shallow Cycle-procedure. The differences are the number of cycles and depth of discharge. The Deep Cycle-test cycle between 80% - 40% of rated capacity. The data from the Deep Cycle-test serves as reference-data. It is expected that the batteries running this test have a higher degradation rate than those running the Shallow Cycle-test. Battery 2, 4, and 8 run the Deep Cycle-test.

Figure 5.2 illustrates the Deep Cycle-procedure. The illustration displays five deep cycles, which are not representative of the actual Deep Cycle-test. The actual test performs 100 deep cycles before running a capacity-check. A long cycling part is to ensure that the battery degradation is mainly due to the cycling part, not the capacity-check.

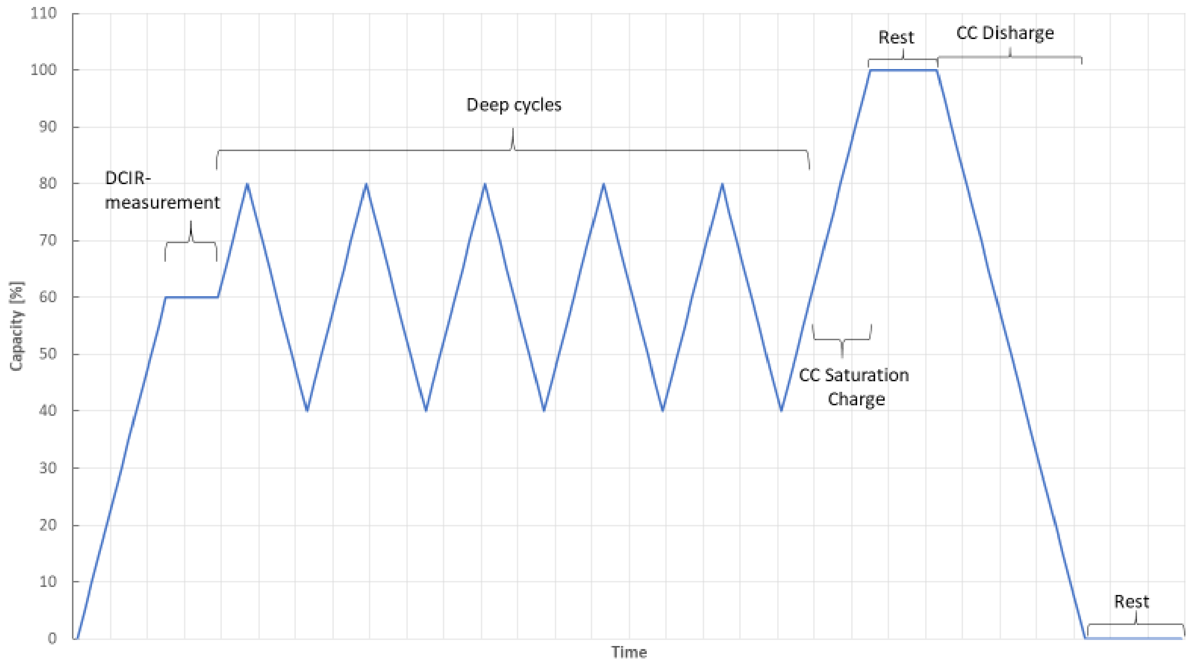

Figure 5.2: The Deep Cycle-procedure. The figure only displays five deep cycles, while the actual test runs 100 deep cycles. The Deep Cycle-recipe is based on this procedure.

5.1.3 Combined Cycle-procedure

The Combined Cycle-procedure is a combination of the Shallow Cycle- and the Deep Cycle-procedure. By adding a slight variation of the shallow cycles (referred to as combined shallow cycles from now on) on top of each other to create a version of the deep cycles (referred to as combined cycles) and thus creating the Combined Cycle-procedure.

The combined shallow cycles charge 10% and discharge 5% or vice versa depending on whether the battery is generally charging or not. The combined cycles cycle between 80% - 40% of rated capacity. The results from the test objects running the Combined Cycle-test are compared to the results from the other Cycle-tests. Battery 3, 6, and 9 from the PC-test are assigned the Combined Cycle-test.

Figure 5.3 shows the Combined Cycle-procedure. The figure illustrates 26 combined shallow cycles and two combined cycles, which is less than in the actual test. The actual test performs 40 combined cycles before running a capacity-check. This amount of cycles ensures that most of the battery degradation is due to cycling, not the capacity-check.

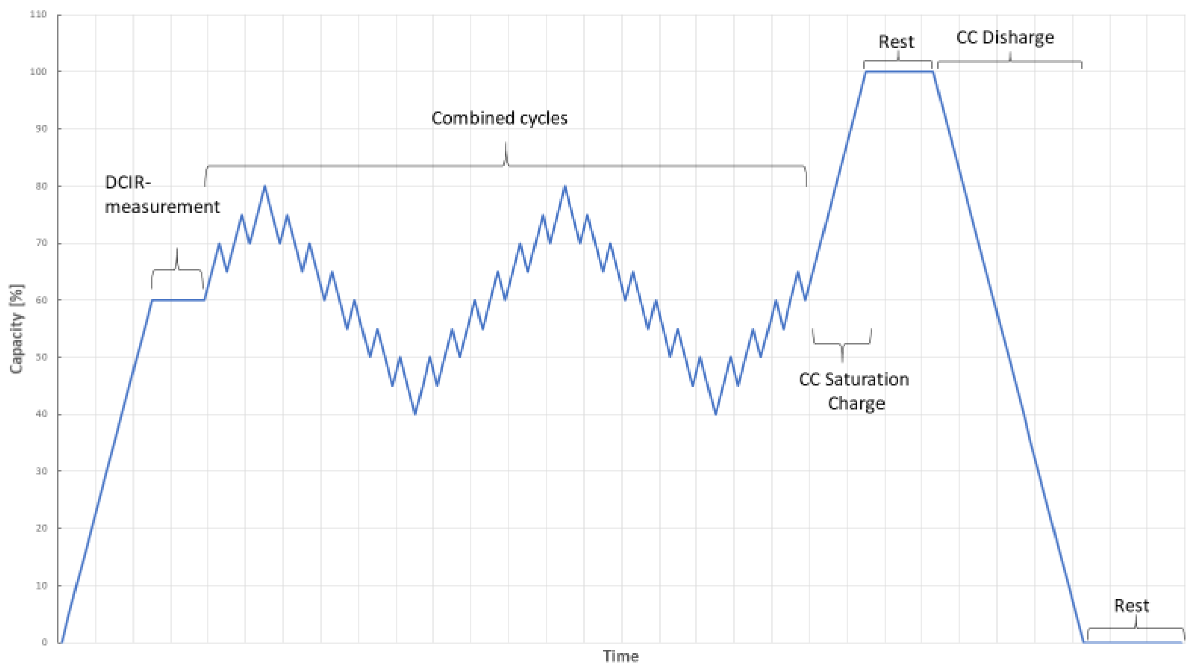

Figure 5.3: The Combined Cycle-procedure. The figure displays two combined cycles and 26 combined shallow cycles, while the actual test performs 40 combined cycles. The Combined Cycle-recipe is based on this procedure.

5.2 Method: Cycle-tests

This section explains every Cycle-recipe. The recipes are created by the Recipe Editor in Battery Pro. The laboratory- and software setup is the same as in section 4.2 Method: Performance- and Capacity-test.

5.2.1 Shallow Cycle-recipe

Every step in the Shallow Cycle-recipe requires a cut-off condition. A cut-off condition is needed for the BTS to move on to the next step in the recipe. The Shallow Cycle-recipe require these cut-off conditions:

- Cut-off when the battery reaches 60% capacity during charge.
- Cut-off when the battery reaches 65% capacity during charge.
- Cut-off when the battery reaches 55% capacity during discharge.
- Cut-off when the battery reaches maximum voltage during saturation charging.
- Cut-off when the battery reaches minimum voltage during complete discharge.
- Cut-off after sufficient resting time.

Voltage levels define the cut-off conditions during charging. The voltages are obtained by charging Battery 1 to 60% capacity and 65% capacity. When the battery reaches these capacities, the voltages are noted down and used as a cut-off condition in the recipe.

The other recipes also require a cut-off condition at 60% capacity. Therefore, the same voltage is used for every recipe.

The cut-off condition for maximum- and minimum voltage is located in the specifications for SB12V2600P-AC, Appendix C.3. These voltages are also used in every recipe.

Energy dispatch defines the cut-off conditions during discharge. Ten percent of the batteries rated capacity equals 3.1775 Wh.

For the battery cells to become properly rested between cycling and capacity-checks, every recipe implements two hours of rest each time.

Table 5.1 shows the cut-off conditions used in the Shallow Cycle-recipe.

Table 5.2 illustrates every step that makes the Shallow Cycle-recipe and Appendix F.2 shows the entire recipe in the Recipe Editor. The recipe is based on the procedure in Figure 5.1.

Table 5.1: Cut-off conditions required to make the Shallow Cycle-recipe for Battery 1, 5 and 7.

Cut-off conditions:	
$V_{60\%}$ [V]	13.533
$V_{65\%}$ [V]	13.561
V_{max} [V]	14.6
V_{min} [V]	8
$E_{10\%}$ [Wh]	3.1775
Rest [s]	7 200

Table 5.2: Shallow Cycle-recipe for Battery 1, 5 and 7. Step 5 and 6 are looped 400 times to perform enough shallow cycles each run. The whole recipe also repeats itself to execute the Shallow Cycle-test twice before ending. This is done by using the Cycle label the same way as the Loop label.

Step No	Step Name	I(A)	Cut-off Condition	Loop label	Loop to	Count	Cycle label	Cycle to	Count	Description
1	Rest		Time >= 7200					b	2	Rest
2	CC Charge	2.5	V > 13.533							Charge up to 60%
3	DCIR Discharge		T1 > 20 T2 > 20							DCIR Discharge
4	DCIR Charge		T1 > 20 T2 > 20							DCIR Charge
5	CC Charge	2.5	V > 13.561		a	400				Charge up to 65%
6	CC Discharge	2.5	Wh > 3.1775	a						Discharge down to 55%
7	CC Charge	2.5	V > 14.6							Saturation Charge
8	CC Charge	1.25	V > 14.6							Saturation Charge
9	CC Charge	0.6	V > 14.6							Saturation Charge
10	CC Charge	0.3	V > 14.6							Saturation Charge
11	CC Charge	0.125	V > 14.6							Saturation Charge
12	Rest		Time >= 7200							Rest
13	CC Discharge	2.5	V < 8				b			Complete Discharge

5.2.2 Deep Cycle-recipe

The Deep Cycle-recipe shares many of the cut-off conditions as the Shallow Cycle-recipe. However, there are two exceptions:

- Instead of cutting off at 65% capacity, cut-off happens at 80% capacity during charge.
- Instead of cutting off at 55% capacity, cut-off happens at 40% capacity during discharge.

The cut-off condition during charge was found by charging Battery 2 to 80% capacity and noting down the voltage. This voltage was used for every battery performing the Deep Cycle-test and Combined Cycle-test.

Energy dispatch still defines cut-off during discharge. The Deep Cycle-test discharges forty percent of the rated capacity each deep cycle. Forty percent of the rated capacity equals to 12.71 Wh.

The other cut-off conditions are the same as in the Shallow Cycle-recipe

Table 5.3 shows the cut-off conditions required to create the Deep Cycle-recipe.

Table 5.4 illustrates every step in the Deep Cycle-recipe, and Appendix F.3 shows how the recipe looks in the Recipe Editor. The recipe is based on the procedure in Figure 5.2.

Table 5.3: Cut-off conditions required to make the Deep Cycle-recipe for Battery 2, 4 and 8.

Cut-off conditions	
$V_{60\%}$ [V]	13.533
$V_{80\%}$ [V]	13.657
V_{max} [V]	14.6
V_{min} [V]	8
$E_{40\%}$ [Wh]	12.71
Rest [s]	7 200

Table 5.4: Deep Cycle-recipe for Battery 2, 4 and 8. Step 5 and 6 are looped 100 times via the loop label-function. The entire recipe is cycled twice to acquire more data each run.

Step No	Step Name	I(A)	Cut-off Condition	Loop label	Loop to	Count	Cycle label	Cycle to	Count	Description
1	Rest		Time >= 7200					b	2	Rest
2	CC Charge	2.5	V > 13.533							Charge up to 60%
3	DCIR Discharge		T1 > 20 T2 > 20							DCIR Discharge
4	DCIR Charge		T1 > 20 T2 > 20							DCIR Charge
5	CC Charge	2.5	V > 13.657		a	100				Charge up to 80%
6	CC Discharge	2.5	Wh > 12.71	a						Discharge down to 40%
7	CC Charge	2.5	V > 14.6							Saturation Charge
8	CC Charge	1.25	V > 14.6							Saturation Charge
9	CC Charge	0.6	V > 14.6							Saturation Charge
10	CC Charge	0.3	V > 14.6							Saturation Charge
11	CC Charge	0.125	V > 14.6							Saturation Charge
12	Rest		Time >= 7200							Rest
13	CC Discharge	2.5	V < 8				b			Complete Discharge

5.2.3 Combined Cycle-recipe

The Combined Cycle-recipe requires more steps than the previous recipes. However, most of the cut-off conditions are the same as in the Shallow- and Deep Cycle-recipes. The exceptions are:

- Energy dispatch and energy absorption define the cut-off conditions during combined shallow cycles, except for charge to 80% capacity.

Ten percent of the rated capacity equals 3.18 Wh, and five percent equals 1.59 Wh. These values are the required cut-off conditions for the combined shallow cycles.

Other cut-off conditions are the same as in the previous two recipes.

Table 5.5 shows every cut-off condition used to create the Combined Cycle-recipe.

Table 5.6 illustrates every step in the Combined Cycle-recipe, and Appendix F.4 shows how the recipe looks in the Recipe Editor. The recipe is based on the procedure in Figure 5.3.

Table 5.5: Cut-off conditions required to make the Combined Cycle-recipe for Battery 3, 6 and 9

Cut-off conditions	
$V_{60\%}$ [V]	13.533
$V_{80\%}$ [V]	13.657
V_{max} [V]	14.6
V_{min} [V]	8
$E_{10\%}$ [Wh]	3.1775
$E_{5\%}$ [Wh]	1.58875
Rest [s]	7 200

Table 5.6: Combined Cycle-recipe. Step 5 – 30 equals one combined cycle and is looped 40 times. The entire recipe is cycled twice to acquire more data.

Step No	Step Name	I(A)	Cut-off Condition	Loop label	Loop to	Count	Cycle label	Cycle to	Count	Description
1	Rest		Time >= 7200					b	2	Rest
2	CC Charge	2.5	V > 13.533							Charge up to 60%
3	DCIR Discharge		T1 > 20 T2 > 20							DCIR Discharge
4	DCIR Charge		T1 > 20 T2 > 20							DCIR Charge
5	CC Charge	2.5	Wh > 3.1775		a	40				Charge up to 70%
6	CC Discharge	2.5	Wh > 1.58875							Discharge down to 65%
7	CC Charge	2.5	Wh > 3.1775							Charge up to 75%
8	CC Discharge	2.5	Wh > 1.58875							Discharge down to 70%
9	CC Charge	2.5	V > 13.657							Charge up to 80%
10	CC Discharge	2.5	Wh > 3.1775							Discharge down to 70%
11	CC Charge	2.5	Wh > 1.58875							Charge up to 75%
12	CC Discharge	2.5	Wh > 3.1775							Discharge down to 65%
13	CC Charge	2.5	Wh > 1.58875							Charge up to 70%
14	CC Discharge	2.5	Wh > 3.1775							Discharge down to 60%
15	CC Charge	2.5	Wh > 1.58875							Charge up to 65%
16	CC Discharge	2.5	Wh > 3.1775							Discharge down to 55%
17	CC Charge	2.5	Wh > 1.58875							Charge up to 60%
18	CC Discharge	2.5	Wh > 3.1775							Discharge down to 50%
19	CC Charge	2.5	Wh > 1.58875							Charge up to 55%
20	CC Discharge	2.5	Wh > 3.1775							Discharge down to 45%
21	CC Charge	2.5	Wh > 1.58875							Charge up to 50%
22	CC Discharge	2.5	Wh > 3.1775							Discharge down to 40%
23	CC Charge	2.5	Wh > 3.1775							Charge up to 50%
24	CC Discharge	2.5	Wh > 1.58875							Discharge down to 45%
25	CC Charge	2.5	Wh > 3.1775							Charge up to 55%
26	CC Discharge	2.5	Wh > 1.58875							Discharge down to 50%
27	CC Charge	2.5	Wh > 3.1775							Charge up to 60%
28	CC Discharge	2.5	Wh > 1.58875							Discharge down to 55%

29	CC Charge	2.5	Wh > 3.1775			Charge up to 65%
30	CC Discharge	2.5	Wh > 1.58875	a		Discharge down to 60%
31	CC Charge	2.5	V > 14.6			Saturation Charge
32	CC Charge	1.25	V > 14.6			Saturation Charge
33	CC Charge	0.6	V > 14.6			Saturation Charge
34	CC Charge	0.3	V > 14.6			Saturation Charge
35	CC Charge	0.125	V > 14.6			Saturation Charge
36	Rest		Time >= 7200			Rest
37	CC Discharge	2.5	V < 8		b	Complete Discharge

5.2.4 Recipe Executor

In the Recipe Editor, the Cycle-recipes are applied to every battery. Table 5.7 illustrates the distribution of batteries across the recipes.

Table 5.7: Distribution of batteries across recipes.

Recipe	**Battery**
Shallow Cycle	1, 5 and 7
Deep Cycle	2, 4 and 8
Combined Cycle	3, 6 and 9

5.2.5 Risk Assessment Measures

The risk assessment measures for the Cycle-tests are the same as in the PC-test.

5.3 Results: Cycle-tests

5.3.1 Recipe procedure

To confirm that the Cycle-test executes the steps in the recipes, Figure 5.4 - Figure 5.6 and Appendix G.1 - Appendix G.9 presents the voltage-, current-, accumulated energy-, and accumulated charge at a random point during the test for each of the Cycle-tests.

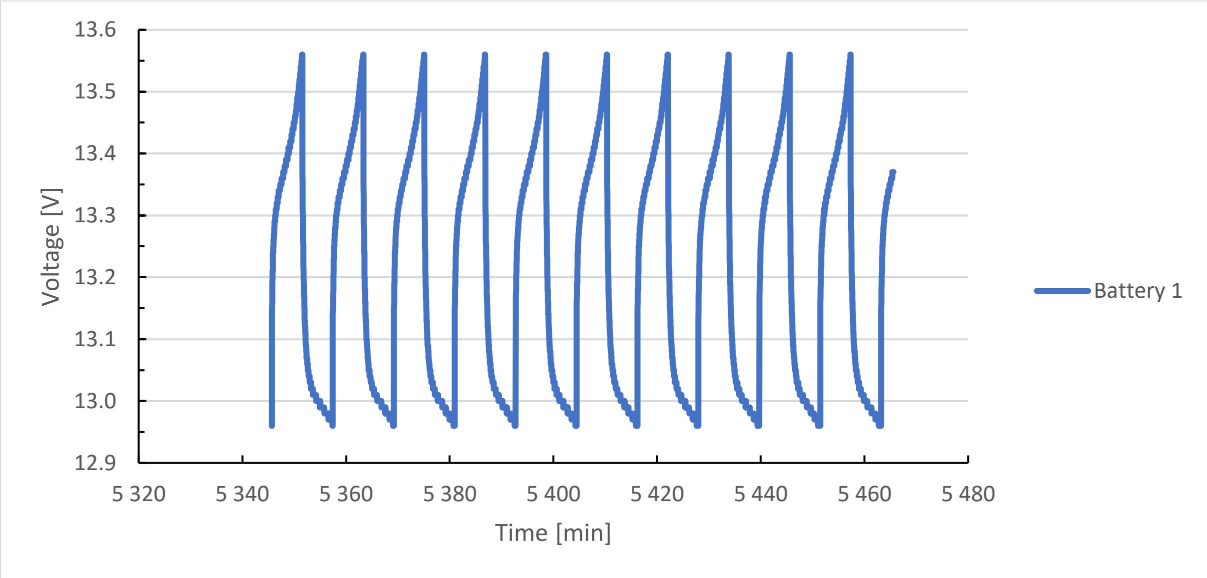

Figure 5.4: Two-hour stream of the battery voltage at a random point during the Shallow Cycles-test.

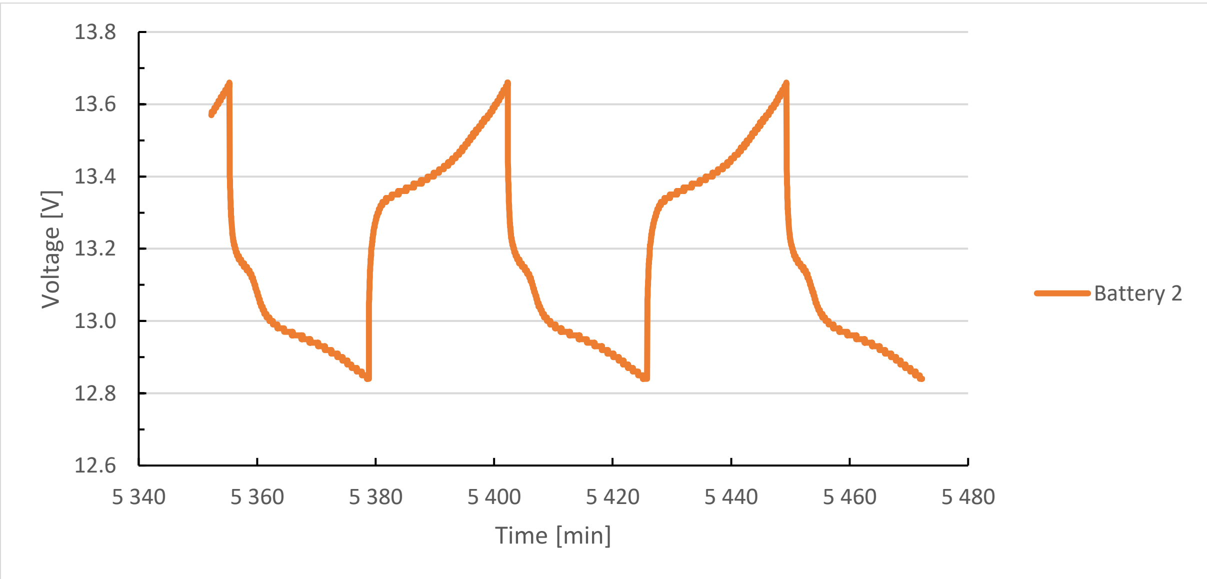

Figure 5.5: Two-hour stream of the battery voltage at a random point during the Deep Cycles-test.

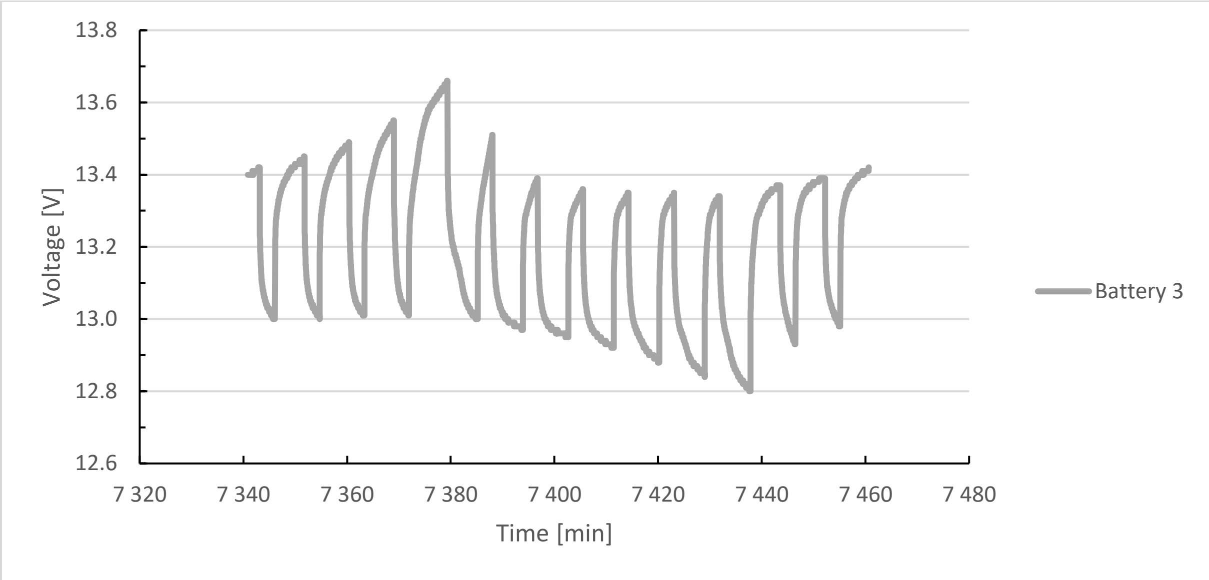

Figure 5.6: Two-hour stream of the battery voltage at a random point during the Combined Cycles-test.

5.3.2 Battery capacity and degradation

Battery capacity

Figure 5.7 shows the capacity decrease for Battery 3, 6, and 9 running the Combined Cycle-test.

Figure 5.8 shows the capacity decrease in percent. The percent is calculated from the battery's initial capacity.

Appendix G.10 and Appendix G.11 illustrates the capacity decrease of Battery 1, 5, and 7 performing the Shallow Cycle-test.

Appendix G.12 and Appendix G.13 shows the capacity decrease of Battery 2, 4, and 8 executing the Deep Cycle-test.

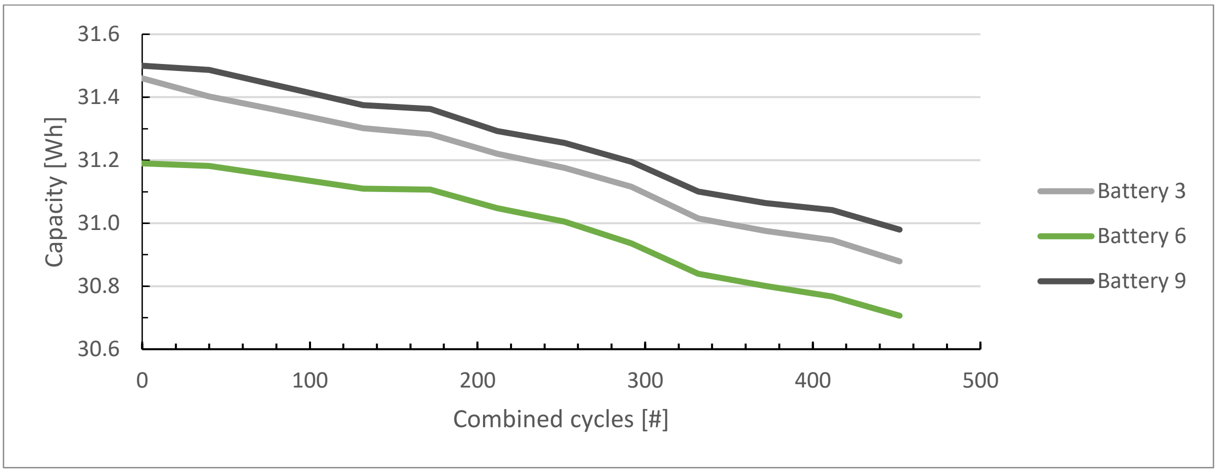

Figure 5.7: Capacity decrease for Battery 3, 6, and 9 executing the Combined Cycle-test. Battery capacity is represented with Wh.

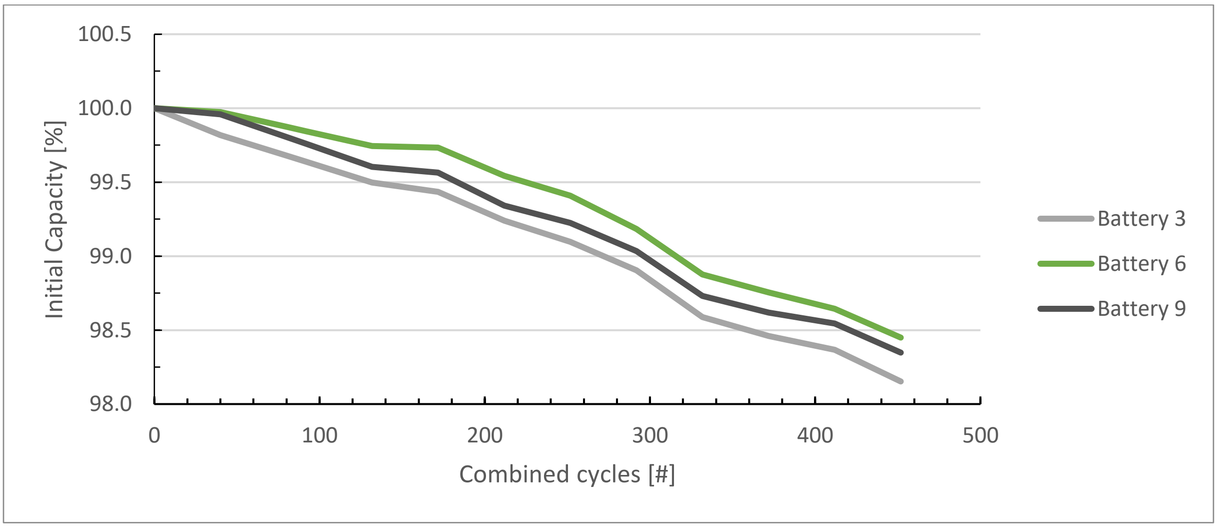

Figure 5.8: Capacity decrease for Battery 3, 6, and 9 executing the Combined Cycle-test. Capacity is represented in percent calculated from the battery's initial capacity.

Battery degradation

Battery degradation describes the battery's lost capacity in Wh.

Full cycles are the number of times the battery has used all its capacity. It does not necessarily need to discharge it all at once, but throughout several cycles. In this report, one full cycle is equivalent to discharging 31.775 Wh, the rated capacity of SB12V2600P-AC.

Table 5.8 is an overview of every battery's cycle-test, initial capacity, number of full cycles, total degradation in Wh, and percentage.

Figure 5.9 illustrates the degradation of every battery. The degradation percentage is calculated from each battery's initial capacity. Appendix G.14 shows every battery's degradation in Wh.

Table 5.8: Overview of battery, Cycle-test, initial capacity, amount of- full cycles, -total degradation in Wh, and percentage. The degradation percentage is calculated from the initial capacity of every battery. The batteries are sorted from most- to least degradation.

Battery	**Cycle-test**	**Initial cap. [Wh]**	**Full cycles [#]**	**Tot. deg. [Wh]**	**Tot deg. [%]**
2	Deep	31.38	463.7	0.86	2.74
4	Deep	31.43	463.0	0.85	2.70
8	Deep	31.51	463.4	0.76	2.41
7	Shallow	31.41	464.7	0.64	2.04
5	Shallow	31.47	464.5	0.64	2.03
1	Shallow	31.42	464.7	0.61	1.94
3	Combined	31.46	464.3	0.58	1.84
9	Combined	31.50	464.6	0.52	1.65
6	Combined	31.19	464.2	0.48	1.54

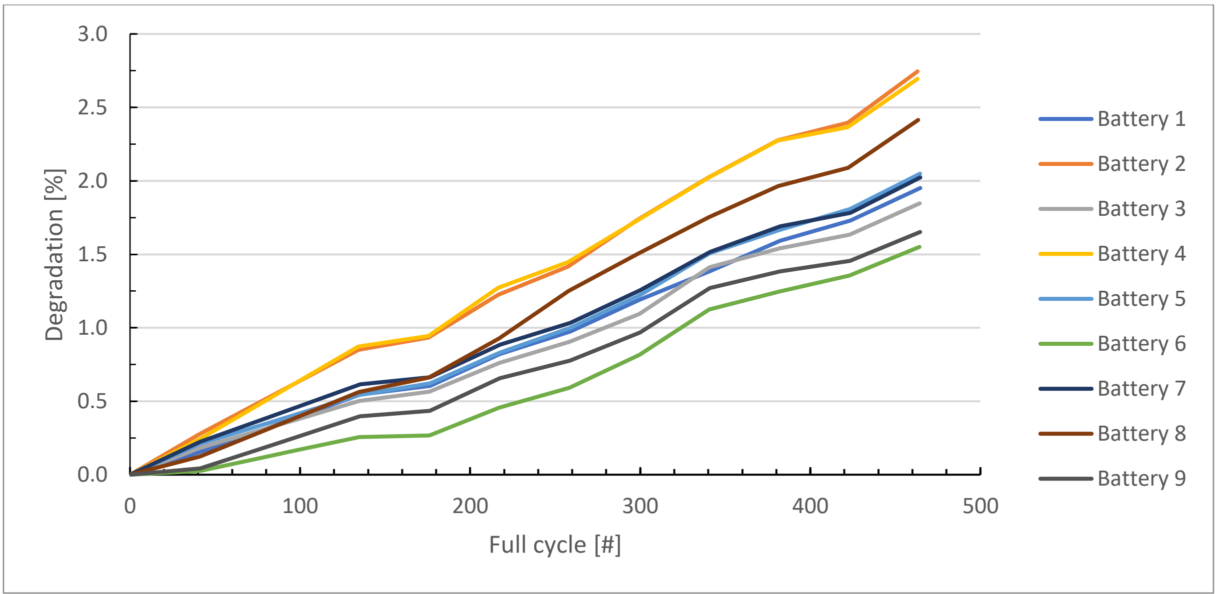

Figure 5.9: Every test object's course of degradation. The degradation percentage is calculated from every battery's initial capacity. Full Cycle is the number of times the battery has discharged a total of 31.775 Wh (the rated capacity).

5.3.3 Battery internal resistance, temperature and losses

Internal resistance

In Figure 5.10, every internal resistance-measurement on Battery 2, 4, and 8 performing the Deep Cycle-test is shown. The internal resistance of the batteries executing the Shallow Cycle-test and the Combined Cycle-test are illustrated in Appendix G.15 and Appendix G.16, respectively.

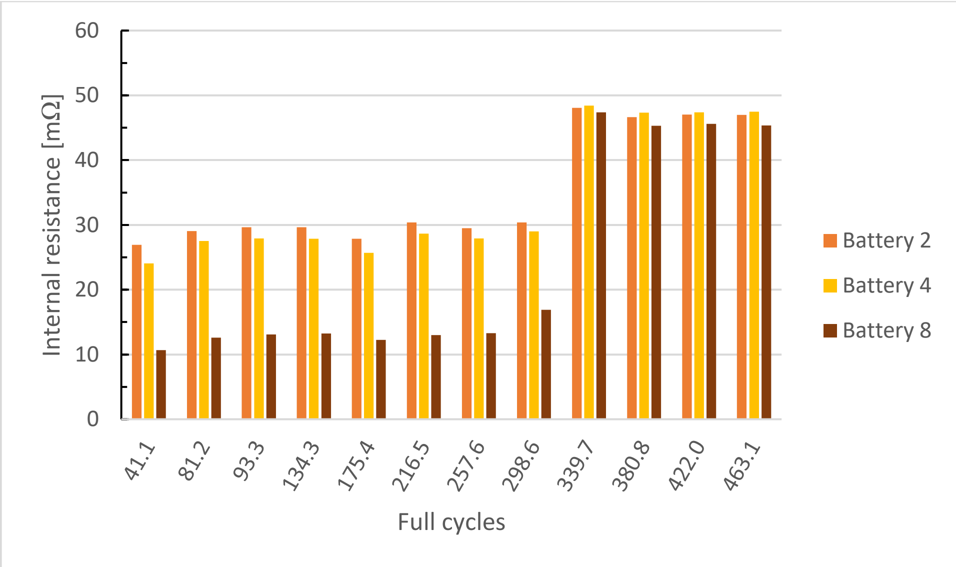

Figure 5.10: Internal resistance for Battery 2, 4, and 8 executing the Deep Cycle-test. The internal resistance is measured during discharge. The number of full cycles comes from Battery 2. However, Battery 8 only differ with 0.3 full cycles at the last measurement.

Temperature

Figure 5.11 shows the maximum temperature recorded for Battery 1, 5, and 7 after each time the Shallow Cycle-test finished. The maximum temperature recorded for the batteries after performing the Deep Cycle-test and Combined Cycle-test is in Appendix G.17 and Appendix G.18, respectively.

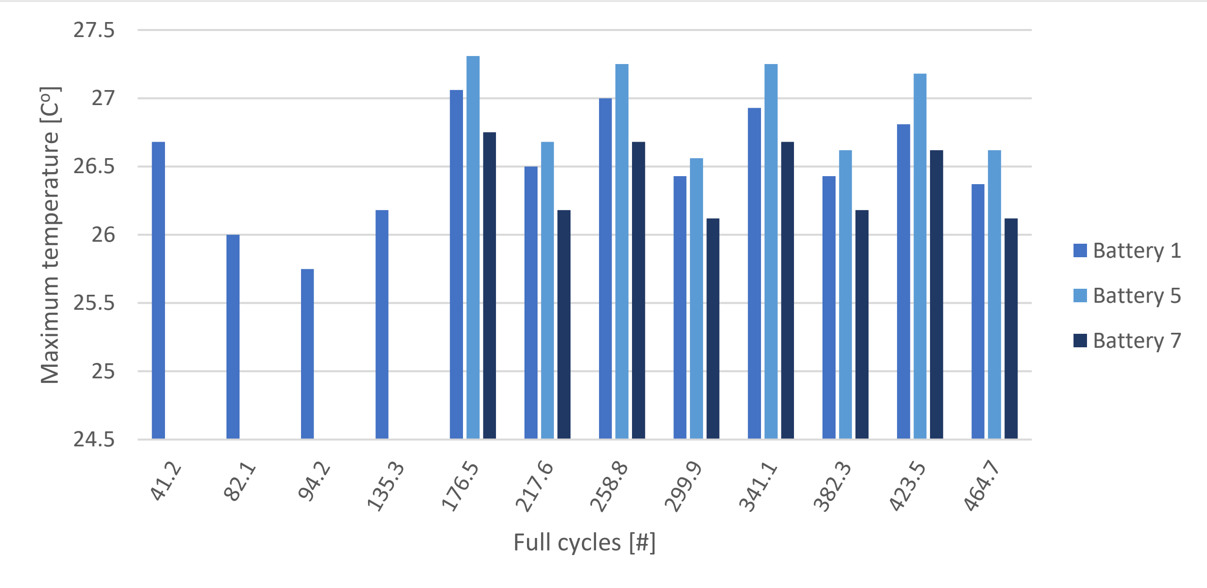

Figure 5.11: Maximum temperature recorded after each time the Shallow Cycle-test is performed for Battery 1, 5, and 7. Unfortunately, Battery 5 and 7 did not have temperature sensors the first couple of runs.

Losses

During the testing procedure, every battery experienced energy losses. These losses are illustrated in Table 5.9, which also shows the total time used and the average power loss. The table is sorted from most- to least losses. Figure 5.12 illustrates every battery's accumulated energy loss, and Figure 5.13 shows the calculated average power loss.

Table 5.9: Total accumulated losses, total time and the average power loss for every battery test object throughout the testing procedure. The batteries are sorted from most- to least total accumulated losses.

Battery	Cycle-test	Total accumulated energy loss [Wh]	Total time [h]	Average power loss [W]
8	Deep Cycle	553.4	887.4	0.62
4	Deep Cycle	549.9	888.5	0.62
2	Deep Cycle	535.1	888.2	0.60
6	Combined Cycle	444.6	887.0	0.50
9	Combined Cycle	442.9	886.2	0.50
3	Combined Cycle	441.7	886.8	0.50
1	Shallow Cycle	414.8	885.5	0.47
5	Shallow Cycle	414.7	885.8	0.47
7	Shallow Cycle	406.3	885.4	0.46

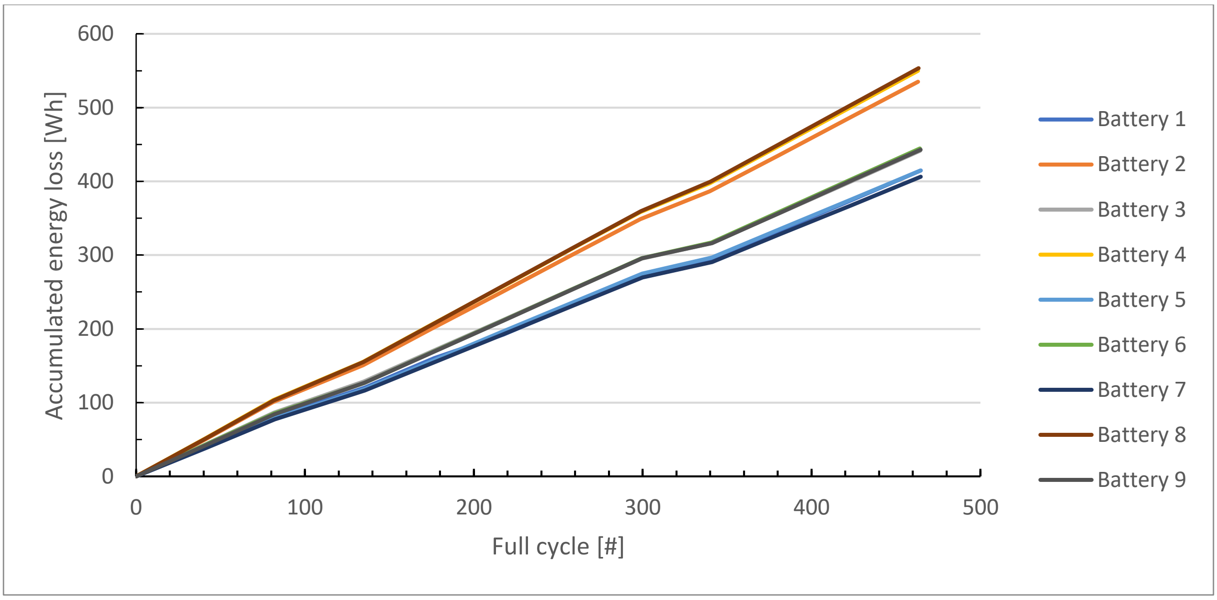

Figure 5.12: Accumulated energy losses in Wh for every battery test object.

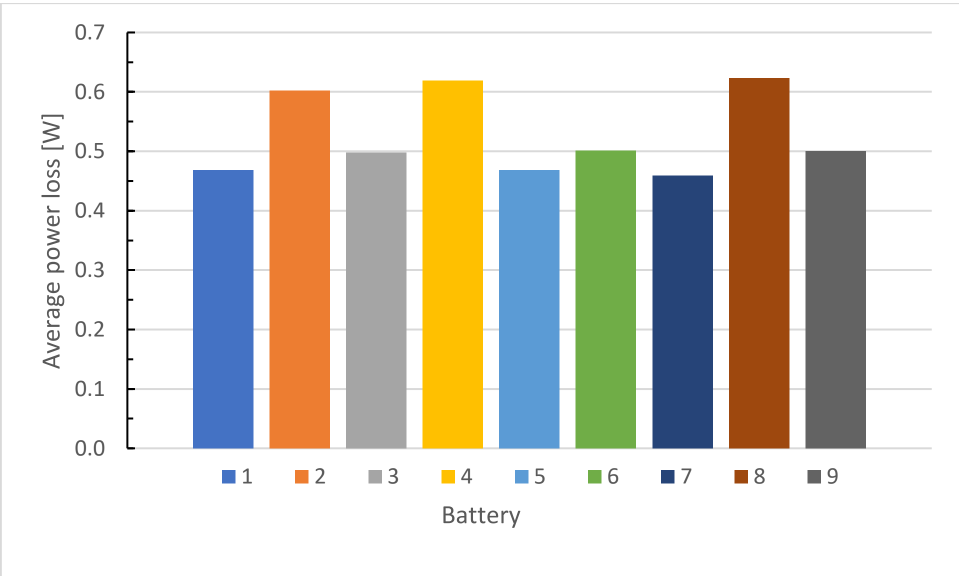

Figure 5.13: Average power loss for every battery test object.

5.4 Observations: Cycle-tests

The batteries performing the Deep Cycle-test experienced most capacity degradation and energy losses. The batteries performing the Combined Cycle-test experienced least capacity degradation, and the batteries executing the Shallow Cycle-test had the least losses.

Every battery experienced an increase in its internal resistance after approximately 340 full cycles. Even Battery 8, which had a relatively low internal resistance 'caught up' with the other batteries.

Battery 5 – 9 did not have a temperature sensor attached until approximately 135 full cycles were performed. Battery 4 did not have a temperature sensor attached between the 82nd and 135th full cycle. Battery 6 has the lowest maximum temperature out of all test objects during every test.

The resting periods are subtracted from the time-measurements in Table 5.9.

Chapter 6. Discussion

Chroma 17020 Regenerative Battery Pack Test System, Softwares and other Equipment

The Battery Test System invested by NTNU for experiments and research on secondary battery technologies is reliable. However, learning to use the equipment was based on *learning by burning* alongside a poorly written manual. The Battery Pro software manual is written very thoroughly, explaining how to execute every command there is, but give little explanation on what the commands do or why. After some hours roaming the different modules in Battery Pro, the software became understandable. There are still many functions and commands that are not explored. An example of this is the *Dynamic Test Mode-*, *Other Test Mode- and External Control Mode-tab* in the Recipe Editor, see Figure 6.1. Some of these functions might have been more suitable for the tasks in this report.

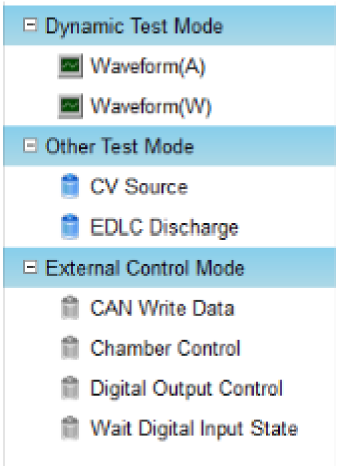

Figure 6.1: Unexplored functions in Recipe Editor, Battery Pro.

Since the Report-module in Battery Pro extracted data-files as csv-files (suitable for Excel and MatLab), it was decided to use Microsoft Excel for data management.

In the Report module, the user can choose which parameters to log and extract. For this master thesis, the parameters logged every second were: Time, voltage, current, charge, accumulated charge, and temperature. The values for voltage, current, and time were used to calculate power, accumulated energy, and SOC. The SOC was calculated with the accumulated energy divided by the battery's rated capacity. This method did not account for losses, but the SOC was solely used to identify voltage cut-off conditions.

Some of the batteries did not have temperature sensors during either the PC-test or a significant part of the Cycle-testing. Four temperature sensors were available from the project thesis done before this master thesis. Six, equal sensors were ordered up. Unfortunately, the manufacturer experienced a flaw in their shipping-routines, causing a delay in the delivery. It was decided to start the Cycle-tests without the sensors to be able to produce enough battery degradation. Battery 4 was equipped with a temperature sensor during the PC-test but got its sensor removed for the service-engineers to put together the new sensors properly.

The test objects, nine new SB12V2600P-AC-batteries performed expectantly.

Performance and Capacity-test

None of the test objects had an actual capacity below 98%, considering capacity in both Wh and Ah. This result indicates that every cell in every test object did not experience fault or damage during production. The batteries have an operating voltage of 13.2 V, and the operating voltage of a standard LiFePO4-cell is 3.2 V – 3.3 V. That means that the SB12V2600P-AC contains four LiFePO4-cells in series per string.

By looking at Figure 4.4 and Appendix E.1 (for capacity in Wh) versus Figure 4.5 and Appendix E.2 (Ah), it becomes clear that the results differ from each other. At higher discharge rates, the results for Ampere-hours do not correlate with the amount of energy that is drawn from the batteries. Thus, capacity is presented in Watt-hours for the rest of the report.

The drop in delivered energy at higher discharge rates can be explained by looking at the voltage profiles in Figure 4.7 and Appendix E.3 - Appendix E.10. At higher discharge, the operating voltage drops. This happens because a higher discharge rate creates more ohmic- (I^2R), hysteresis- and polarization losses inside the battery cells [15]. Hence a decrease in energy output.

Figure 4.8 and Appendix E.11 shows that the internal resistances for almost every test object is similar. The anomaly is Battery 8, which had about half of the internal resistance as the other batteries. The reason is not certain, but the low resistance correlates with a relatively high capacity, compared to the other test objects.

At 1 C discharge rate, the four batteries equipped with temperature sensors were able to dissipate the generated heat. None of the batteries exceeded 25 ^{o}C. Appendix E.14 shows that Battery 4 did not generate more heat with a higher discharge rate, as Battery 1, 2, and 3 did. A poorly fastened temperature sensor could be the reason.

Realistic profiles

In section 5.1 Introduction: Cycle-test, it is mentioned that every Cycle-procedure cycle around 60% to make the profiles more realistic. The most natural average capacity to cycle around is 50%. However, it is always preferable to have more capacity in the batteries before service, hence making the Cycle-procedures more realistic.

Distribution of batteries on recipes

Before initiating the Cycle-tests, three batteries had to be distributed to each Cycle-recipe. A key objective of the distribution was that the total capacity of the batteries on each of the Cycle-tests should not differ too much. Another objective was that the batteries with relatively high- or low capacity were distributed equally. Table 6.1 shows the distribution of batteries and total capacity on each Cycle-test.

Table 6.1: Distribution of batteries across the Cycle-tests. Every Cycle-test has similar total capacity. The initial capacity is sorted from highest to lowest capacity on each test.

Test	**Shallow Cycle**	**Deep Cycle**	**Combined Cycle**
Batteries	1, 5, and 7	2, 4, and 8	3, 6, and 9
Init. cap. [Wh]	31.47	31.51	31.50
	31.42	31.43	31.46
	31.41	31.38	31.19
Total cap. [Wh]	94.3	94.32	94.15

Cut-off conditions

The voltages used in the recipes contained many decimals. This is because lithium-ion batteries have a relatively flat voltage-curve. A small difference in voltage can be a significant difference in capacity [15].

The method used to obtain cut-off conditions during charge is not ideal. An ideal method is to use a relaxed open-circuit voltage as a function of SOC. However, for the battery cells to become completely relaxed could take several hours or days [15].

Confirmation of the Cycle-recipes

The cut-off conditions in the Cycle-recipes were confirmed by checking the parameter streams in the results.

Firstly, Figure 5.4 shows that every shallow cycle charge Battery 1 to 13.561 V, which is the cut-off condition used in the Shallow Cycle-recipe. Appendix G.4 shows that every shallow cycle releases 3.18 Wh from Battery 1.

Secondly, Figure 5.5 shows that every deep cycle charges its batteries to 13.657 V. Appendix G.5 shows that every deep cycle release approximately 12.71 Wh.

Lastly, the Combined Cycle-recipe is set to absorb and dispatch 3.18 Wh and 1.59 Wh. The Combined Cycle-recipe is also set to charge to 13.657 V. These conditions are confirmed in Appendix G.6 and Figure 5.6, respectively.

The results confirm that every Cycle-test obeys the cut-off conditions set in the recipes.

More sophisticated Combined Cycle-recipe

The Combined Cycle-recipe on Table 5.6 could be made with fewer steps and thus be more sophisticated by entering three loop-labels. The first loop is repeating Step 5 and 6 two times. The second loop is repeating Step 10 and 11 six times. Lastly, looping Step 23 and 24 three times and thus completing one combined cycle. This method would reduce the Combined Cycle-recipe with twelve steps.

Unfinished Cycle-test runs

Because of various reasons, some of the Cycle-test runs were not able to finish correctly. The first run stopped when opening the Battery Simulator-software. When this happened, every battery was completing the last capacity check before finishing. The unfortunate stop affected the results. For instance, none of the batteries were able to reveal their actual capacity by the end.

The second run was stopped after a few hours due to a safety mistake. One of the temperature sensors ethernet cable was not long enough to be placed safely along the side of the laboratory floor. Therefore, some of the results have an entry on approximately 94 full cycles. However, the number of cycles, internal resistance, and maximum temperature was recorded regardless.

Table 5.2, Table 5.4 and Table 5.6 show that every Cycle-recipe is set to repeat itself before finishing. This is not true for the third run. Due to the unfinished first run, the third run was set not to repeat itself. This run finished on approximately 135 full cycles.

After the third run, the recipes were set to repeat themselves again. All other runs finished adequately.

Degradation and degradation rate

The degradation results in Figure 5.9 and Appendix G.14 show that every battery on each Cycle-test has a similar degradation rate. Looking at Table 5.8, the battery with the highest degradation after almost 465 full cycles was Battery 2 with 0.86 Wh. In comparison, the battery with the least degradation, Battery 6, lost 0.48 Wh of its initial capacity. The difference between the two batteries is not much. However, when comparing the degradation rate, Battery 2 has a degradation rate of 79.2% higher than Battery 6.

Estimated EoL for batteries on each Cycle-test

According to [17], batteries reach EoL when the actual capacity is 80% or less of rated capacity. The SB12V2600P-AC has reached EoL when it delivers 25.42 Wh or less. According to Appendix C.3, the SB12V2600P-AC should be able to perform over 4 000 cycles before reaching EoL. This report was not able to perform 4 000 full cycles on any of the test objects. However, an average and linear estimation on the number of full cycles the batteries on every Cycle-test would perform is conducted below. The degradation percentages and the number of full cycles are gathered from Table 5.8.

Shallow Cycles:

$$d_{Shallow,avg} = \frac{d_1 + d_5 + d_7}{3} = \frac{1.95\% + 2.03\% + 2.04\%}{3} = 2.007\%$$

$$f_{Shallow,avg} = \frac{f_1 + f_5 + f_7}{3} = \frac{464.7 + 464.5 + 464.7}{3} = 464.63\ full\ cycles$$

$$n_{EoL,Shallow} = \frac{464.63}{2.007\%} * 20\% \approx 4\ 630\ full\ cycles$$

Deep Cycles:

$$d_{Deep,avg} = 2.617\%$$

$$f_{Deep,avg} = 463.17\ full\ cycles$$

$$n_{EoL,Deep} \approx 3\ 540\ full\ cycles$$

Combined Cycles:

$$d_{Combined,avg} = 1.683\%$$

$$f_{Combined,avg} = 464.37\ full\ cycles$$

$$n_{EoL,Combined} \approx 5\ 520\ full\ cycles$$

Where:

d_i: Degradation percentage for Battery i.
$d_{y,avg}$: Average degradation percentage for batteries performing Cycle-test y.
f_i: Number of full cycles performed by Battery i.
$f_{y,avg}$: Average number of full cycles for batteries performing Cycle-test y.
$n_{EoL,y}$: Estimated number of full cycles before reaching EoL for batteries performing Cycle-test y.

According to the calculations above, the batteries executing the Shallow Cycle-test and Combined Cycle-test could perform over 4 000 full cycles. However, the calculations are assuming a linear degradation rate. The degradation rate would probably accelerate with more testing and cause the batteries to reach EoL in fewer full cycles than calculated.

Internal resistance

Only internal resistance during discharge was included in the Cycle-test results. This is because the internal resistance during charge was almost equal to the discharge.

In the results for internal resistance (Figure 5.10, Appendix G.15 and Appendix G.16), there is a sudden jump in resistance for every test object after approximately 340 full cycles. Even Battery 8, which measured approximately half of the other battery's internal resistance in the PC-test and first 300 full cycles of the Cycle-test, experienced a 280% increase in internal resistance. The sudden increase in internal resistance could be explained by increased SEI-layer inside the cells.

As batteries age with cycle life and calendar life, its internal resistance increases. This leads to a decrease in capacity and increased heat generation and losses.

The sudden increase in internal resistance does not make an apparent impact on the other results.

Temperature

The maximum temperature was recorded with a sampling rate of twice every Cycle-test run (except the second- and third run, which because of the reasons explained above, only sampled the maximum temperature once).

The batteries achieved maximum temperature during saturation charging (the second run achieved maximum temperature during cycling). According to results in Figure 5.11, Appendix G.17 and Appendix G.18, the increased internal resistance after 340 full cycles did not increase the maximum temperature recorded. It could have increased the average temperature during cycling. Unfortunately, this is not known.

The Cycle-recipes were set to repeat themselves, running the test twice before finishing. According to the results, the battery temperature was higher during the first run-through than the second. This is visible in the figures from the 176^{th} full cycle and onward. It is unknown why this happened, but a memory-effect in the cells could explain it.

Losses and how to obtain losses.

Table 5.9 and Figure 5.12 show that the Deep Cycle-test accumulated most energy losses, while the Shallow Cycle-test accumulated the least energy losses.

Every Cycle-test cycle with fixed current of 1 C. The remaining variable is the voltage, which is highest in the Deep Cycle-test and the Combined Cycle-test. These tests charge up to 13.657 V, while the Shallow Cycle-test charge up to 13.561 V. This could explain why the Shallow Cycle-test had less losses than the rest.

It is unknown exactly why the Deep Cycle-test generates more losses than the Combined Cycle-test, but the number of switches with the highest voltage could explain it. The Deep Cycle-test execute 2.5 times more switches with 13.657 V, which could be a reason why it generates more losses than the Combined Cycle-test.

As mentioned in this chapter, the accumulated energy was calculated from the measured-voltage, current, and time. The batteries start- and end the Cycle-tests in a fully discharged state. Ideally, the accumulated energy from the results would read zero at the end of every test. However, the batteries lose energy during charge and discharge, which must be compensated during charge. This compensation is visible in the data when the battery is fully discharged. The compensation for losses is visible in Appendix G.4 as the accumulated energy increases after every cycle.

Facts and thoughts

Table 6.2 illustrates the discovered facts from the Cycle-test results.

Table 6.2: Facts from the Cycle-test results.

Cycle-test	Battery	Fact
Shallow	1, 5, and 7	• Accumulated least energy losses • Lowest average power loss
Deep	2, 4, and 8	• Highest degradation rate • Accumulated most energy losses • Highest average power loss
Combined	3, 6, and 9	• Lowest degradation rate • Highest maximum temperature recorded (Battery 3) • Lowest maximum temperature recorded (Battery 6)

With the observations shown in Table 6.2, it becomes clear that the Cycle-test that degrades its batteries the most is the Deep Cycle-test. The Combined Cycle-test degrades its batteries the least. Both Cycle-tests cycle between 80% and 40% of rated capacity. The differences are the number of changes in current direction and depth of discharge.

The smaller the depth of discharge, the longer the battery lasts [28]. This is true when comparing the Deep Cycle-test with the Combined Cycle-test. It is also true when comparing the Shallow Cycle-test with the Combined Cycle-test. The Shallow Cycle-test has a 10% depth of discharge throughout the cycling-procedure. The Combined Cycle-test has either 10% or 5%, making the average depth of discharge 7.5%.

Chapter 7. Conclusion

Chroma 17020 Regenerative Battery Pack Test System proved to be both reliable and ingenious once having sufficient experience with the necessary functions.

The results from the Performance and Capacity-test revealed that every test object performed adequately and had not experienced any form of errors during production.

Estimating battery life is an intricate procedure that is dependent on many factors. The results from the Cycle-tests show that the higher the depth of discharge, the higher the rate of degradation.

More research and experiments with a focus on the depth of discharge are required to develop a hypothesis on a possible methodology to estimate battery life.

Chapter 8. Further Work

- Perform tests with more realistic load variation models.
- Further research the impact on battery life with Cycle-tests containing different depth of discharges.
- Compare the degradation results to simulations performed by one or several suitable battery life estimators.
- A better understanding of all functionalities of the Chroma 17020 Regenerative Battery Pack Test System.

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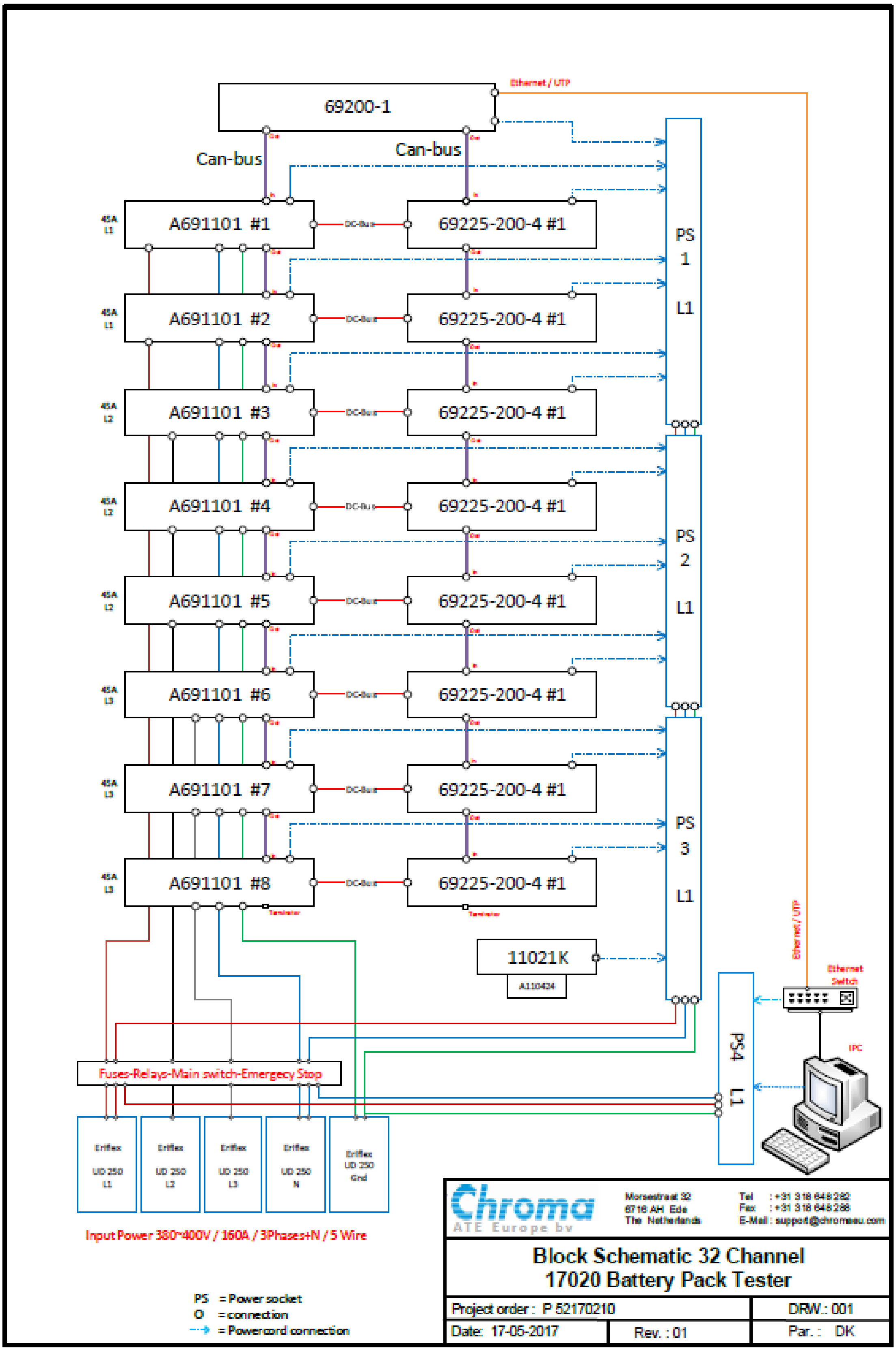
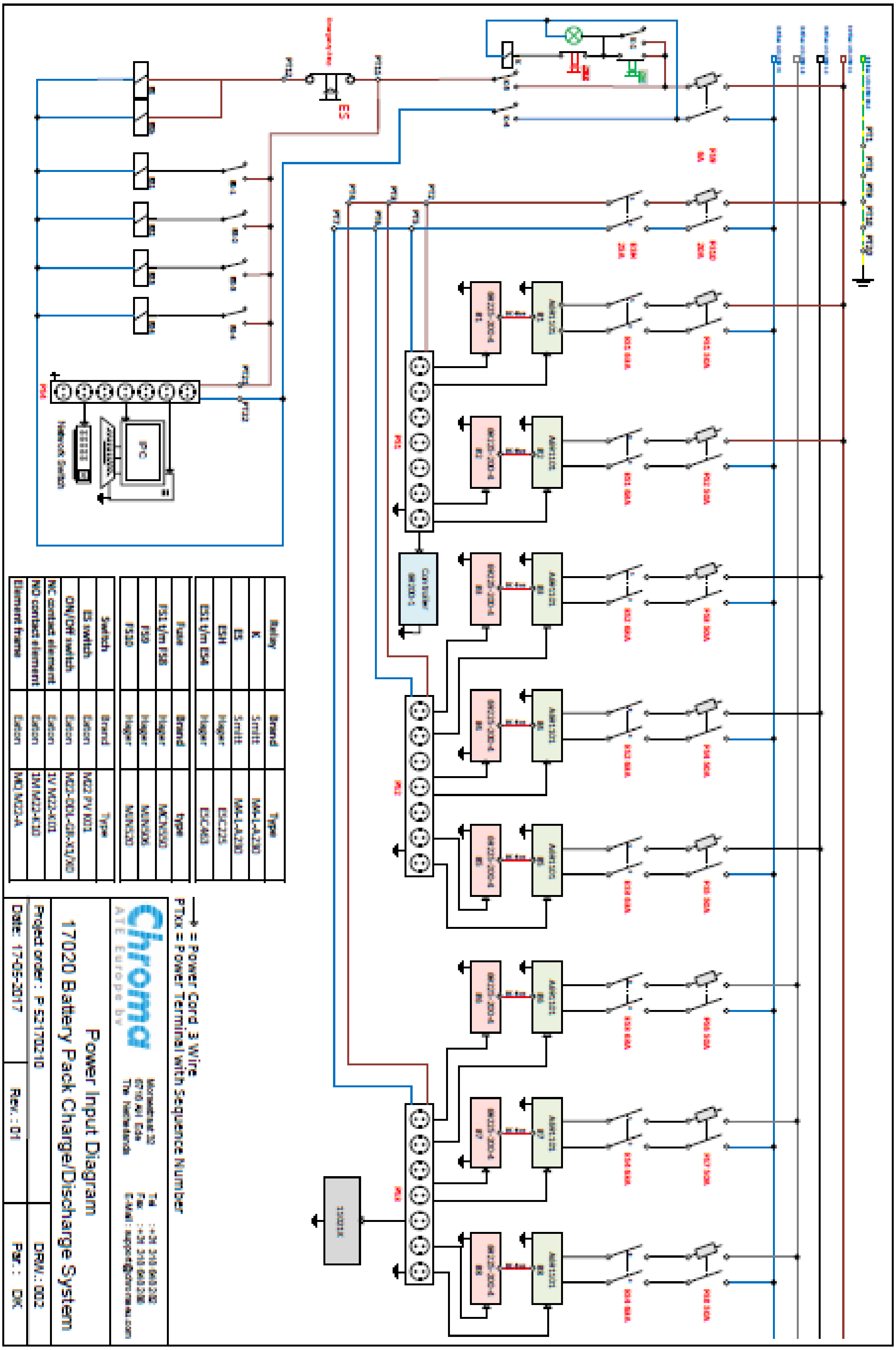
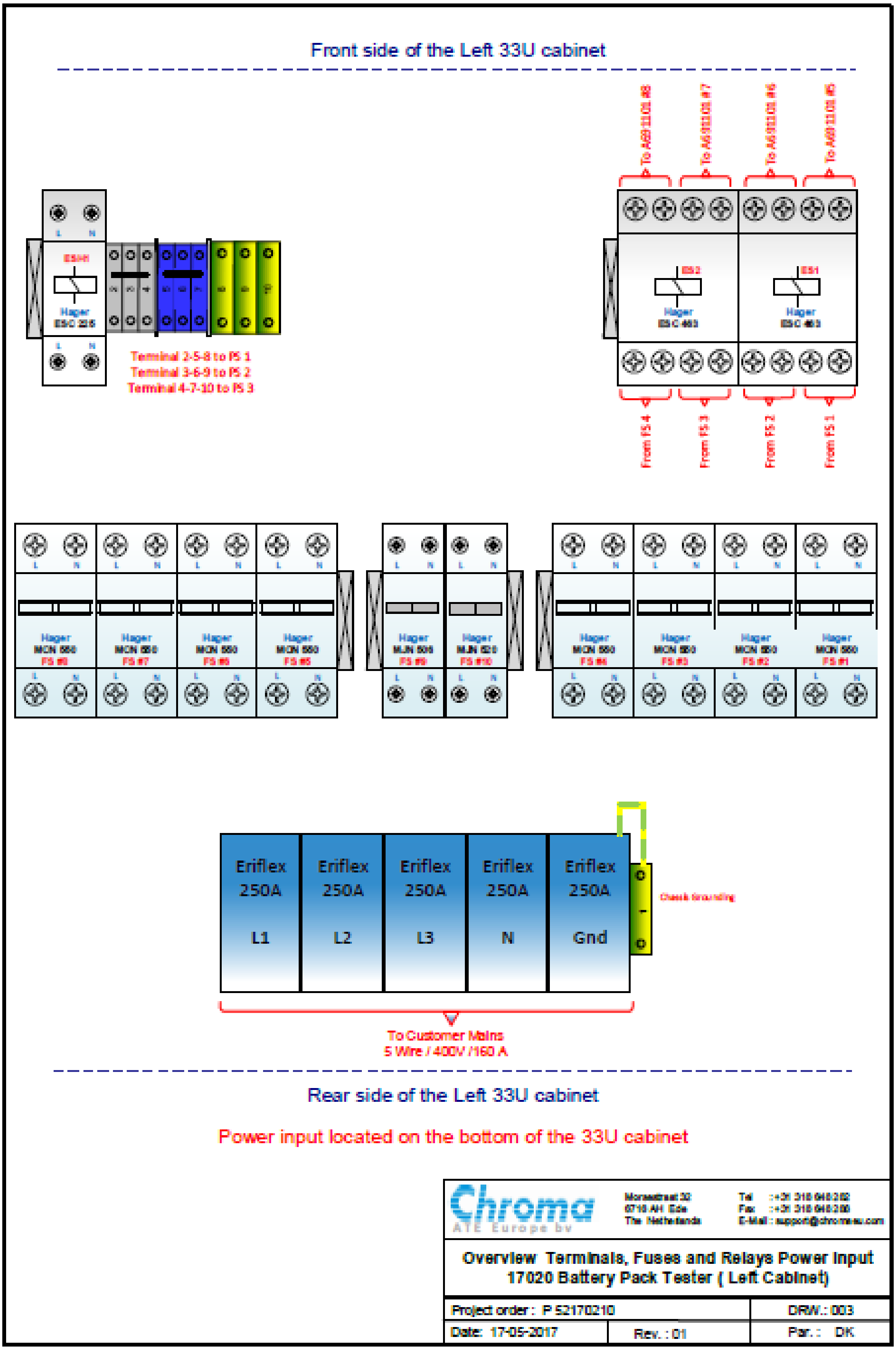
Appendix A. Chroma Battery Test System



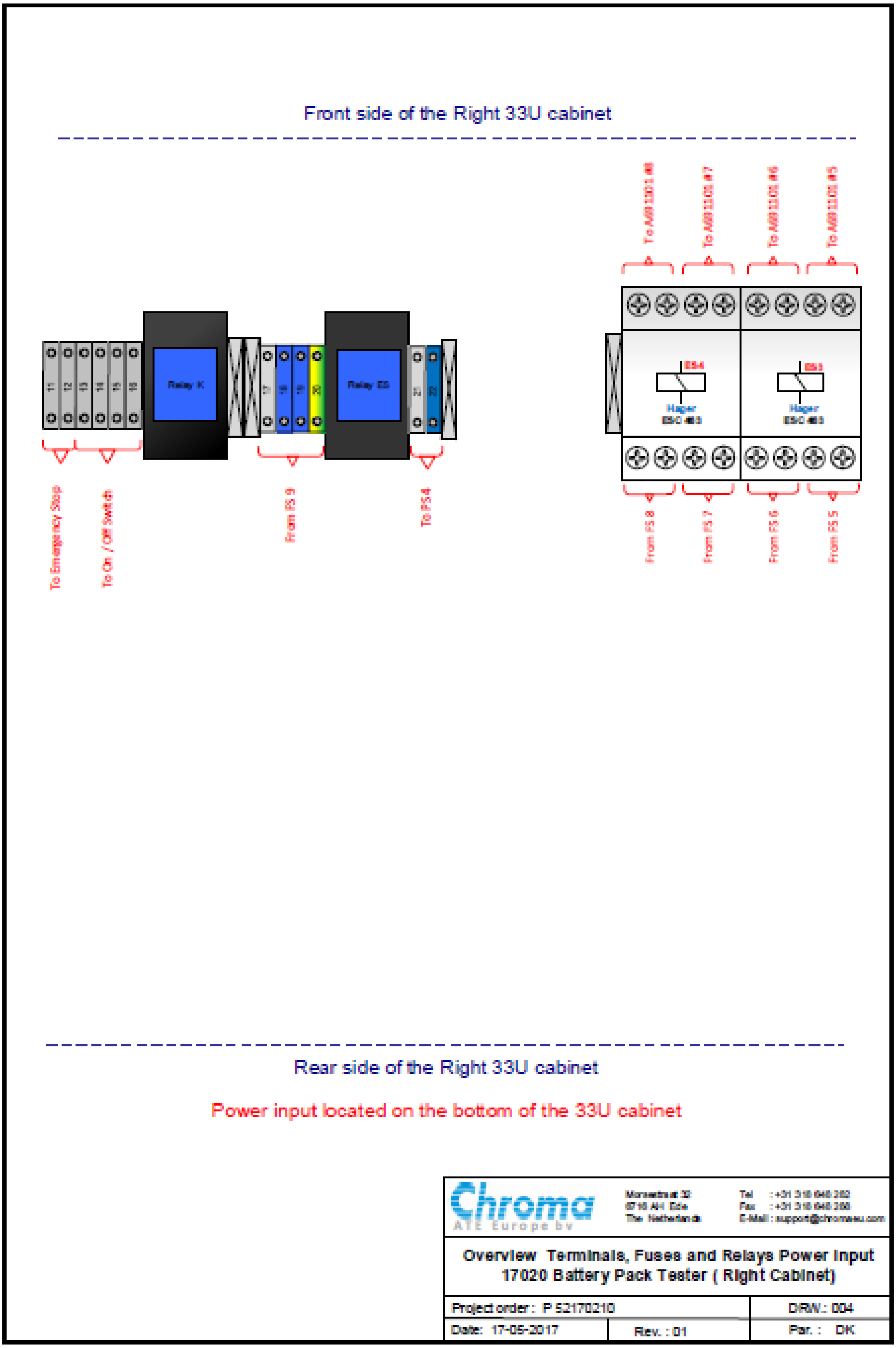
Appendix A.1: BTS Block Schematic.



Appendix A.2: BTS Power Input Diagram.

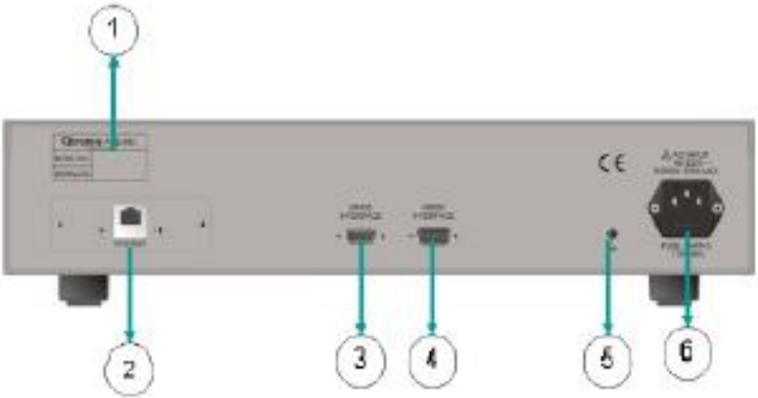


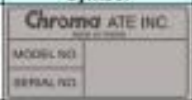
Appendix A.3: BTS Overview Terminals, Fuses and Relays Power Input. Left Cabinet.



Appendix A.4: BTS Overview Terminals, Fuses and Relays Power Input. Right Cabinet.

Overview Connections Controller 69200-1



Item	Symbol	Description
1		***Label:*** The label contains model no. and serial no.
2		***ETHERNET Connector:*** The remote controller uses ETHERNET bus via this connector to connect PC for remote operation.
3		***Interface(69100):*** The A69110 uses 15pin D-SUB cable to connect it in order to communicate with CSU.
4		***Interface(69200):*** The 69206-60-8 uses15pin D-SUB cable to connect it in order to communicate with CSU.
5		***Grounding:*** This terminal allows the user to ground the device.
6		***AC Power Socket:*** The AC power cord inputs A/C power source by connecting this socket to input stage.

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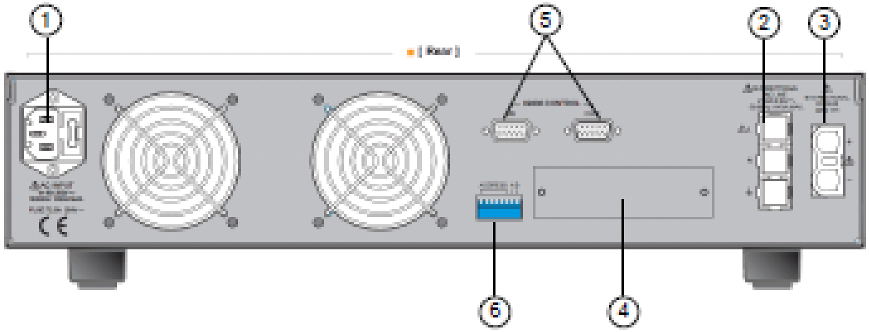
Overview Controller Connections 69200-1
17020 Battery Pack Tester

Project order : P 52170210		DRW.: 005
Date: 17-05-2017	Rev. : 01	Par. : DK

Appendix A.5: BTS Overview Controller 69200-1.

Overview DC/AC Bi-direction Converter 10KW

For Bi-Direction Converter 1~8



Item	Name	Description
1	Auxiliary Power Input	AC source input (single phase) within the range of 90V-250V.
2	I/O Terminal Case for the Mains (Single phase)	It has input/output terminal inside to connect the Mains (single phase) to Anderson 75A connector for power input.
3	I/O Terminal Case (DC BUS)	It has input/output terminal inside to connect the DC BUS to Anderson 50A connector for power input. The connector outputs power to 69206-60-8.
4	Optional Device	It installs the optional connector purchased when using RS485 or Ethernet for remote control.
5	69200 Control	It is a 15-pin DSUB female connector. The command transmits back and forth in between the digital controllers of 69200-1 (option) for operation. If more than one A691101 is paralleled, 15-pin D-SUB is also uses to connect the A691101 in series and the end of the network needs to connect a termination resistor.
6	DIP Switch Address	It sets the hardware machine address. To ensure the system to work normally, Address = 1 must be set for one A691101

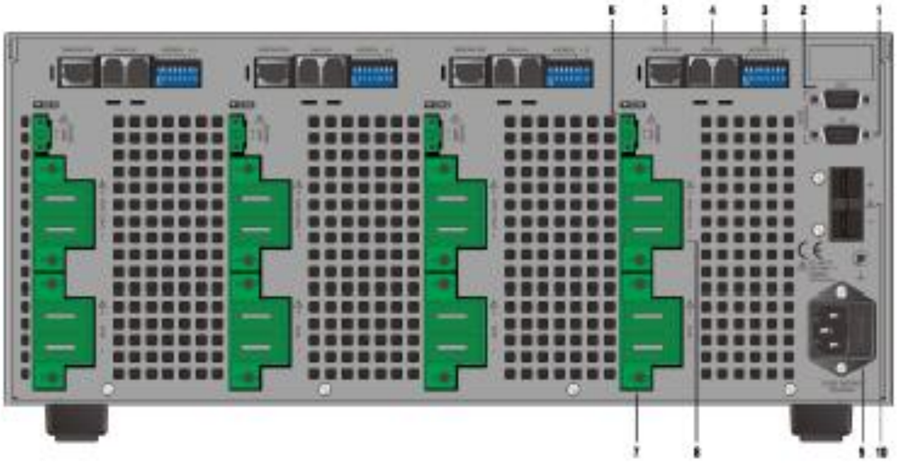
Overview DC/AC Bi-direction Converter A691101
17020 Battery Pack Charge/Discharge Tester

Project order: P 52170210	DRW.: 006
Date: 17-05-2017 Rev.: 01	Par.: DK

Appendix A.6: BTS Overview DC/AC Bi-Directional Converter A691101.

Overview 69225-200-4 Regenerative Charge / Discharge Tester

For 69225-200-4 # 1~8



Item	Name	Description
1	69200 CONTROL Input	It connects 69200-1 controller(IN) via D-Sub.
2	69200 CONTROL Output	It connects 69200-1 controller(OUT) via D-Sub.
3	ADDRESS	By using toggle switch to input channel number and set terminator. PIN / Description: 1 ADDRESS 1 2 ADDRESS 2 3 ADDRESS 3 4 ADDRESS 4 5 ADDRESS 5 6 ADDRESS 6 7 PARALLEL TERMINATOR 8 N/A
4	PARALLEL	After connecting, the tester is with output parallel function, output current is for current sharing.
5	TEMPERATURE	It returns measurement temperature reading via temperature sensor board.
6	RMT SENSE	It connects to load terminal for compensating drop which caused by line resistance. Be sure connector terminal "+" of RMT Sense line connects to "+" terminal on rear panel, connector terminal "-" of RMT Sense line connects to "-" terminal on rear panel. Don't connect polarity reversely.
7	Charge/Discharge	Charge/discharge terminal on charge/discharge tester, before plugging in please ensure RMT Sense line connected. The system default is single output. If dual output function is enabled (coordinating with software), this terminal is discharge port.
8	CHARGE	This is charge port for charge/discharge tester when enabling dual output function (coordinating with software). Before plugging in please ensure RMT Sense line connected. It doesn't be used if dual output function is disabled.
9	AC INPUT	The mains is inputted from the socket, the range is 100V~240V, 50/60Hz 150VA MAX.
10	DC BUS	This is input connection terminal for connecting A691101 output (420V).

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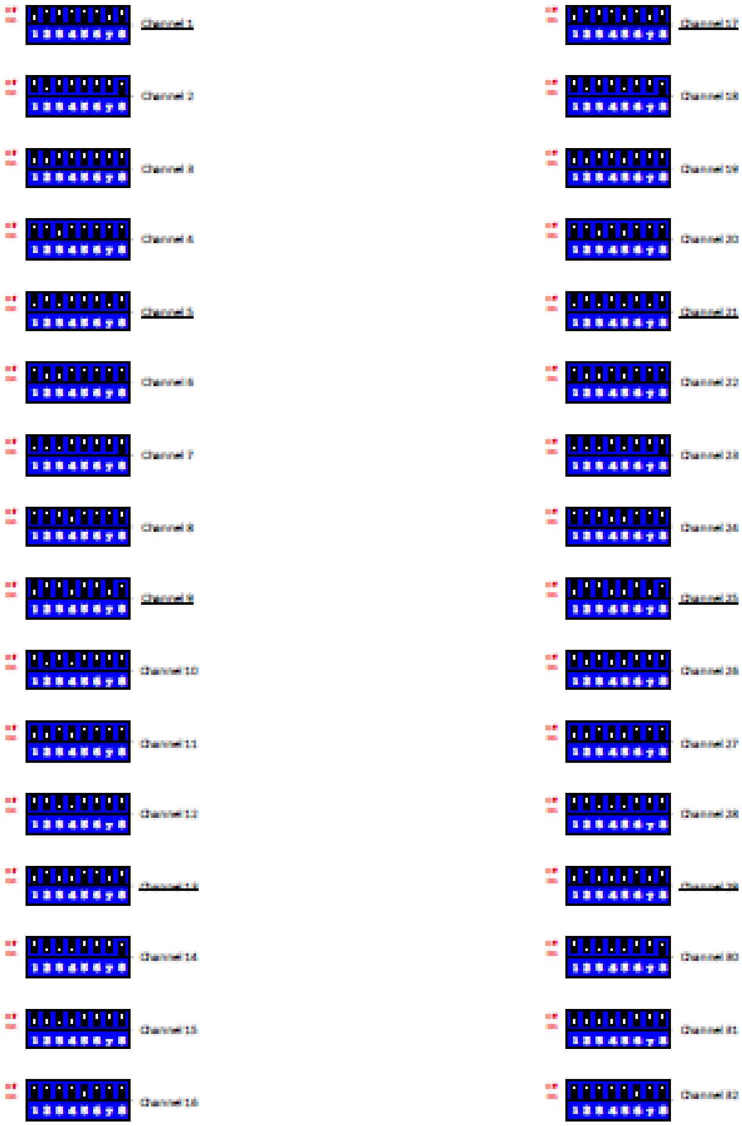
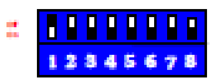
Overview Reginerative Ch/DisC Tester 69225-200-4 17020 Battery Pack Charge/Discharge Tester		
Project order : P 52170210		DRW.: 007
Date: 17-05-2017	Rev. : 01	Par. : DK

Appendix A.7: BTS Overview Regenerative Charge/Discharge Tester 69225-200-4.

Overview Dip-switch setting for Channels 69225-200-4





PIN	Description
1	ADDRESS 1
2	ADDRESS 2
3	ADDRESS 3
4	ADDRESS 4
5	ADDRESS 5
6	ADDRESS 6
7	PARALLEL TERMINATOR
8	N/A

Channel xx=Parallel Terminator is On (undefined)
for
Ch. 1-5-9-13-17-21-25-29

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Overview Dip Switch Settings Reginerative Ch/DisC Tester 69225-200-4

Project order : P 52170210		DRW.: 008
Date: 17-05-2017	Rev. : 01	Par. : DK

Appendix A.8: BTS Dip Switch Settings.

Instruments at 17020 Battery Pack Tester 52170210					
Item	Description	Brand name	Model name	Key specification	Serial number
1	Charge/ Discharge Controller	Chroma	69200-1	Controller	692001000350
2	DC / AC Bi direction Converter	Chroma	A691101	Converter #1-10KW	A69110100582
3	DC / AC Bi direction Converter	Chroma	A691102	Converter #2-10KW	A69110100583
4	DC / AC Bi direction Converter	Chroma	A691103	Converter #3-10KW	A69110100584
5	DC / AC Bi direction Converter	Chroma	A691104	Converter #4-10KW	A69110100585
6	DC / AC Bi direction Converter	Chroma	A691105	Converter #5-10KW	A69110100586
7	DC / AC Bi direction Converter	Chroma	A691106	Converter #6-10KW	A69110100589
8	DC / AC Bi direction Converter	Chroma	A691107	Converter #7-10KW	A69110100592
9	DC / AC Bi direction Converter	Chroma	A691108	Converter #8-10KW	A69110100594
10	Charge / Discharge Tester	Chroma	69225-200-4	Ch./Dis. Tester 200V/30A / 2,5 kW / 4 Ch.	69225AC00132
11	Charge / Discharge Tester	Chroma	69225-200-4	Ch./Dis. Tester 200V/30A / 2,5 kW / 4 Ch.	69225AC00134
12	Charge / Discharge Tester	Chroma	69225-200-4	Ch./Dis. Tester 200V/30A / 2,5 kW / 4 Ch.	69225AC00135
13	Charge / Discharge Tester	Chroma	69225-200-4	Ch./Dis. Tester 200V/30A / 2,5 kW / 4 Ch.	69225AC00136
14	Charge / Discharge Tester	Chroma	69225-200-4	Ch./Dis. Tester 200V/30A / 2,5 kW / 4 Ch.	69225AC00138
15	Charge / Discharge Tester	Chroma	69225-200-4	Ch./Dis. Tester 200V/30A / 2,5 kW / 4 Ch.	69225AC00139
16	Charge / Discharge Tester	Chroma	69225-200-4	Ch./Dis. Tester 200V/30A / 2,5 kW / 4 Ch.	69225AC00140
17	Charge / Discharge Tester	Chroma	69225-200-4	Ch./Dis. Tester 200V/30A / 2,5 kW / 4 Ch.	69225AC00143
18	LCR Meter	Chroma	11021K	LCR meter 1 KHZ	1102120000866
19	Industrial PC	Terra	Industrial PC	IPC with Win 7 19 Inch Rack Mount	R5007243
				Incl. Mouse and scandinavian keyboard	
	Monitor	Acer	V176L BMD	17" PC Monitor	MMLZFEE005643002598531
	Win 7			PI: 00371-OEM-8992671-00339	
20	Ethernet Switch	TP-Link	TL-SF 1008D	8 port Ethernet Switch	-

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Used Instruments at
17020 Battery Pack Tester

Project order : P 52170210		DRW.: 009
Date: 17-05-2017	Rev. : 01	Par. : DK

Appendix A.9: Complete list of components.

Appendix B. Battery Test System, by SINTEF Energy Research

SINTEF

National Smart Grid Laboratory:

Battery test system

INTENDED USE

- Investigations of :
  - battery performance
  - battery degeneration due to cycling and aging
- Use in National Smart Grid Laboratory test setups as:
  - battery (emulated)
  - variable DC-load or DC-source (controlled power, current or voltage source/sink)

MAIN TECHNICAL DATA

- 32 independent channels , each 200V/30A/2.5kW
- Paralleling of channels gives up to 200V/960A/80kW
- Battery energy discharge alternatives:
  - regeneration to grid
  - charge battery on other channel
- Battery measurements:
  - DC internal resistance measurement (DCIR)
  - AC impedance up to 1000Hz (LCR-meter)
- DC side is galvanic isolated from AC grid
- 2-kvadrant operation on DC side:
  - positive and negative current
  - positive voltage
- DC-side protected against:
  - short circuit
  - battery reverse polarity connection
- Test program can be recovered after power outage and test can be continued from the point it was stopped.

SOFTWARE FUNCTIONALITY

- Test cycles can be created and utilized for each channel or channel groups:
  - constant voltage, current or power mode
  - constant resistance mode (discharge only)
  - arbitrary test cycles
  - complex drive cycle testing with dependency on measured voltage or current
  - cycles downloaded from Excel
- Programmable protection functions:
  - high / low battery voltage
  - high current
  - high temperature

COMMUNICATION INTERFACE

- Software system can be remotely controlled via network connection (LAN)
- System hardware can in addition be controlled by Labview driver and SCPI (Standard Commands for Programmable Instruments)

DATA LOGGING

- Logging and storage of measurements (10ms)
- Internal data storage provided to avoid loss of data in the event of loss of power or communication to computer
- Export of logged data to
  - personalized reports
  - files in PDF/CSV/TXT format

LOCATION

- Energy Laboratory, Room F0057, Elektro building E/F, at NTNU in Trondheim, Norway
- System is equipped with wheels and can (in principle) be moved to other locations if needed
- Climate chamber (0.6m^3) available in same room.
- Battery test system can be integrated in test setups in the main laboratory of the National Smart Grid Laboratory via installed power and control cables.

HIGHER VOLTAGE AND HIGHER POWER

- Tailored test set-ups using in-house power electronic converters and a grid emulator can be used to perform tests that requires higher voltage or higher power.

SINTEF

FAKTAARK — SINTEF

KONTAKTPERSON:

Olve Mo
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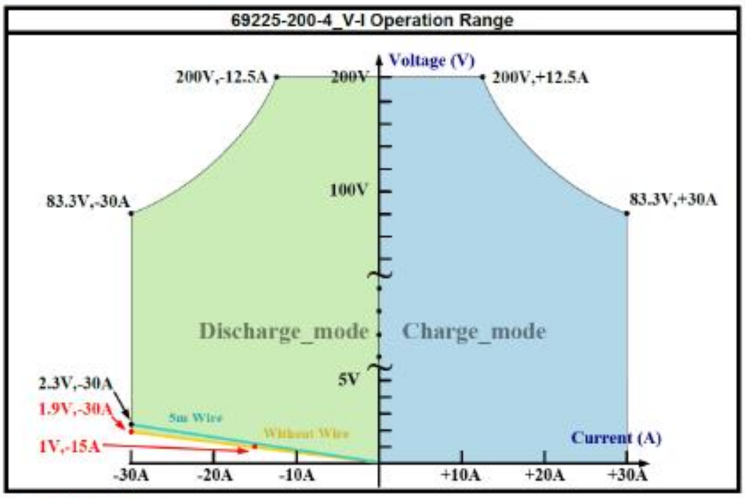
olve.mo @sintef.no

28.06.2017

Appendix B.1: Page 1 of SINTEF Energy Research summary of the BTS. [29]



Operation range

Four wire connection for each channel to allow compensation of voltage drop along cable

Software control

SYSTEM DETAILS

- 1x Chroma 69200-1 Charge/discharge Controller
- 8x Chroma 69225-200-4 Regenerative Charge/ discharge tester 200V/30A/2.5kW/4 Channels
- 8x Chroma DC/AC A691101 Bidirectional controller
- 1x Chroma 11021-K LCR Meter 1kHz
- 1x Chroma A110242 Battery tester ESR Test kit
- Computer with Battery Pro Software

Appendix B.2: Page 2 of SINTEF Energy Research summary of the BTS. [29]

Appendix C. Specifications

Model	**A691101**
Phase	1
DC-to-AC (current output mode)	
Input Voltage Range	400-440Vdc
Input Current Range	0-28A
Output Voltage Range	190-250Vac
Output Current Range	45A
Output Current THD	< 5%
Output Power Range	10KVA
Output Power Factor	> 0.9
AC-to-DC(voltage output mode)	
Input Voltage Range	190-250Vac
Input Current Range	45A
Input Power Factor	> 0.9
Output Voltage Range	400-440Vdc
Output Current Range	0-28A
Output Power Range	10KVA
Measurement for AC power	
Voltage accuracy	0.4% rdg + 0.4% rng
Voltage resolution	0.1V
Current range	45A
Current accuracy	0.8% rng
Current resolution	0.01A
Power accuracy	0.8% rdg + 0.8% rng
Power resolution	0.1W
Input AC Power	
Voltage range	90V – 250V
Power (VA)	<120VA
Others	
Protection	UVP, OCP, OVP, OPP, OTP, FAN_LOCK
Efficiency (Typical)	90%
Interface	RS-485, Ethernet
Temperature	
Operation	0°C - 40°C
Storage	-40°C - 85°C
Safety & EMC	CE
Dimension (H x W x D)	2U height
Weight	30kg / 66.14 lbs

Appendix C.1: Specifications of AC/DC Bi-Directional Converter A69110. [24]

Model	69225-200-4
Channel	4
Charge Mode	
Voltage Range	0-200Vdc
Maximum Current	30A
Max Power	2.5KW
CC Mode Accuracy	0.1% stg.+ 0.05% F.S.
Current Resolution	5mA
CV Mode Accuracy	0.1% stg.+ 0.05% F.S.
Voltage Resolution	5mV
CP Mode Accuracy	0.2% stg.+ 0.1% F.S.
Power Resolution	0.5W
Discharge Mode	
Voltage Range	0-200Vdc
Maximum Current	30A
Max Power	2.5KW
CC Mode Accuracy	0.1% stg.+ 0.05% F.S.
Current Resolution	5mA
CV Mode Accuracy	0.1% stg.+ 0.05% F.S.
Voltage Resolution	5mV
CP Mode Accuracy	0.2% stg.+ 0.1% F.S.
Power Resolution	0.5W
Measurement	
Voltage Range	0-200Vdc
Voltage Accuracy	0.02% rdg.+ 0.02% F.S.
Voltage Resolution	5mV
Current Range	12A/30A
Current Accuracy	0.1% rdg.+ 0.05% rng.
Current Resolution	3mA
Power Range	2500W
Power Accuracy	0.12% rdg.+ 0.07% F.S.
Power Resolution	0.3W
Temperature Range	0-90°C
Temperature Accuracy	±2°C
Temperature Resolution	0.1°C

Appendix C.2: Specifications of Regenerative Charge/Discharge Tester 69225. [25]

lithium batteries

BE IN CHARGE

DATASHEET SUPER B 2600P-AC

SB12V2600P-AC

Light-weight, high-performance, safe and reliable lithium-ion starter battery, especially developed for motorsports. This battery equals a lead-acid battery of 5 to 7Ah, provided the alternator's maximum current doesn't exceed the battery's maximum charge capacity of 10A. Designed in a standard rally casing. Suitable for 12V systems and for use in extreme environments.

LIGHTWEIGHT POWER

With a weight of only 0,46kg or 1.01lb, the SB12V2600P-AC starter battery saves up to 80% in weight in comparison to traditional lead-acid batteries and is only 1/3 of the size of a conventional battery. This improves not only the performance of your vehicle but also helps to increase the fuel economy.

The starter battery offers a high level of power, super-fast charging and a long, maintenance-free service life. It also has a stable and flat discharge which means you have over 80% of the batteries capacity available and you can leave your vehicle unattended for a much longer period compared to a lead-acid battery.

PERFORMANCE

- Super-fast charging
- Lightweight
- Longer service life, up to 4000 cycles
- Incredible small size
- Low self-discharge
- High temperature operating range

SAFETY

Super B batteries are based on Lithium Iron Phosphate technology (LiFePO4). This is the safest Lithium technology available today. On top of that our bespoke casing and electronics further increase safety and durability.

ENVIRONMENT

Super B batteries do not contain lead. The LiFePO4 technology is an environmental-friendly energy storage solution.

3-YEAR WARRANTY

Super B's 3-year warranty offers the best peace of mind. It is the benefit of years of continuous engineering improvement and proven experience with all of our batteries in the harshest environments.

USE

Please take this advice into account while using the battery:

1. Do not jump start.
2. Use a correct charger.
3. Make sure the battery does not get deeply discharged. If the battery has no charge remaining when you check it, consider it to be damaged. Do not attempt to recharge or use it.
4. This battery is specially developed for motorsport. If you want to use it on road, please consult Super B

TECHNICAL SPECIFICATIONS

SKU/EAN13	8718531360006
Battery Designation	4IFpR27/66
Height (mm)	83,50 / 84,50
Diameter (mm)	NA
Width (mm)	113.50/114.50
Thickness (mm)	34,50 / 35,50
Energy (Wh)	31,775
Nominal voltage (V) at 50% SoC, 0.2C discharge	12.71
Charge method	CCCV
Charge voltage (V)	14,3...14,6
Max. charge current (A)	10
Rated capacity (Ah)	2,5
End-of-discharge voltage at max. 10C (V)	8
Max. continuous discharge current (A)	40
Discharge pulse current (A) (1 second)	136A (54C)
EqPb (Equals Lead-acid battery)	5 to 7Ah
Operating temperature range	-30°C to +55°C
Storage temperature range short term (1 month)	-20°C to +45°C
Storage temperature long term (>1 month)	-10°C to +25°C
Cycle life at 1C charge/discharge	>1000
Cycle life at C3 charge/discharge	>4000
Weight	0,460kg

SUPER B LITHIUM POWER B.V. | DEMMERSWEG 3 | 7556 BN HENGELO | THE NETHERLANDS

Appendix C.3: Datasheet SB12V2600P-AC [1].

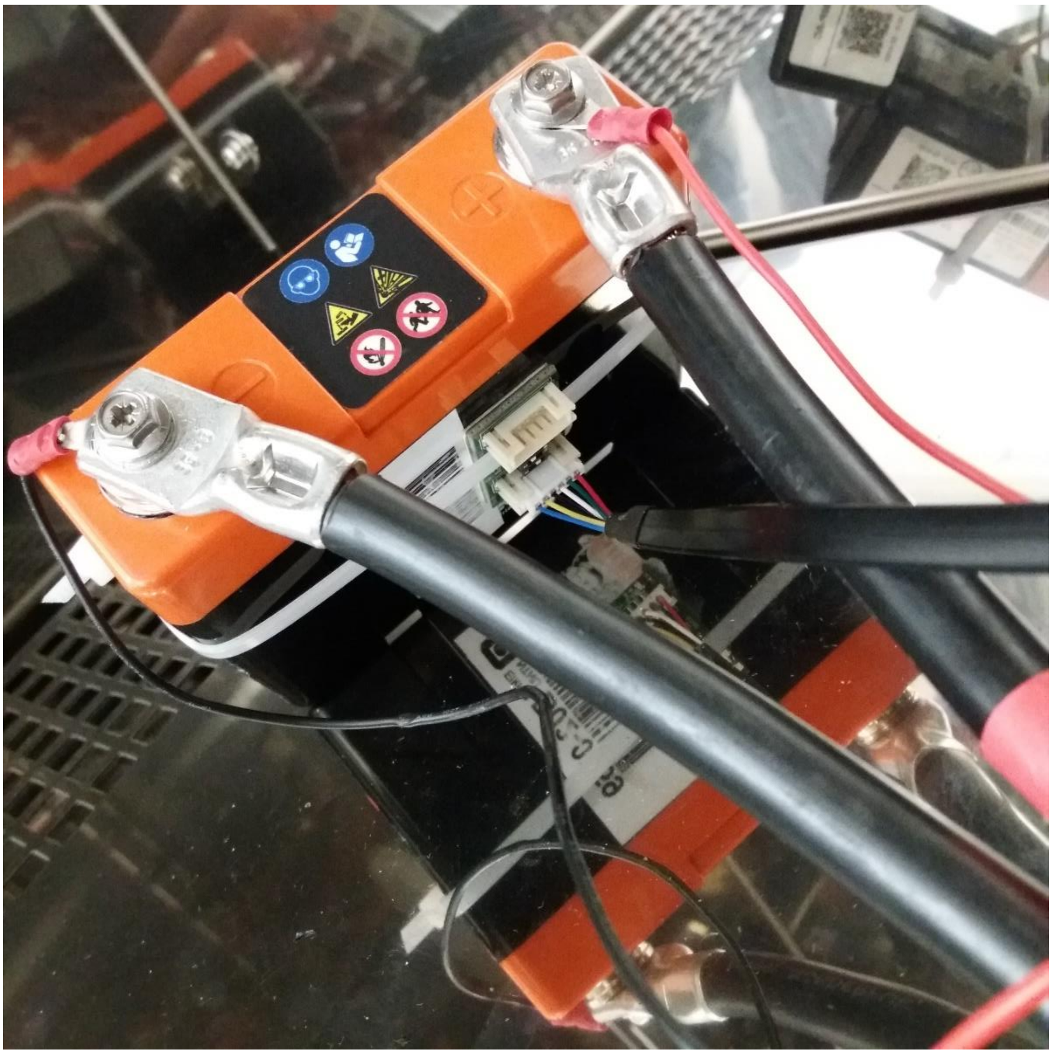
Appendix D. Pictures of laboratory setup

Appendix D.1: Rear view of Tester modules.

Appendix D.2: Tester channel cables.

Appendix D.3: ACS Discovery climate chamber.

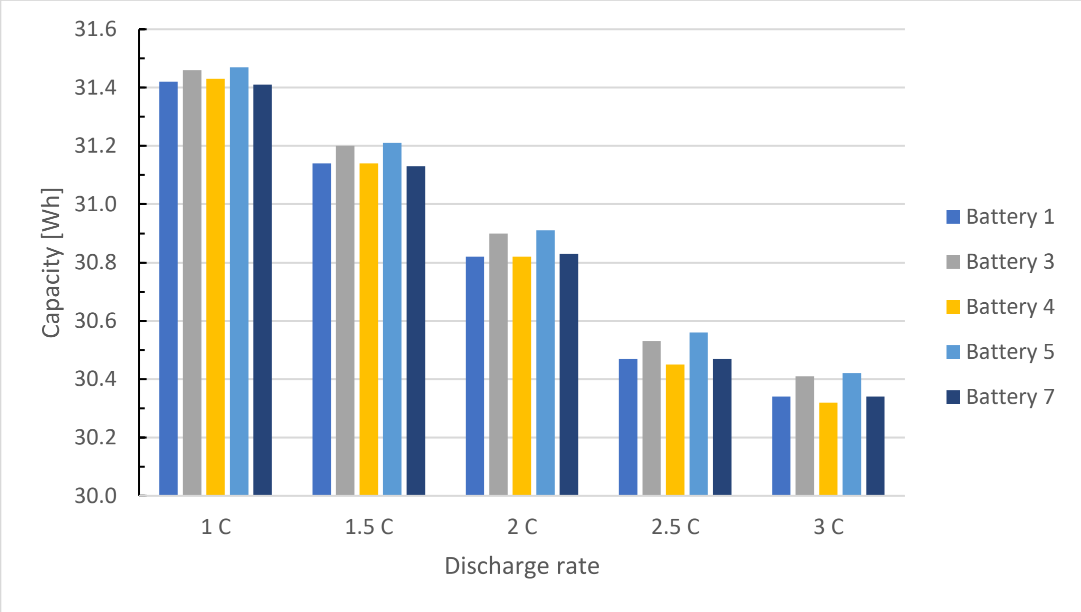
Appendix D.4: Nine SB12V2600P-AC placed inside the ACS Discovery climate chamber.



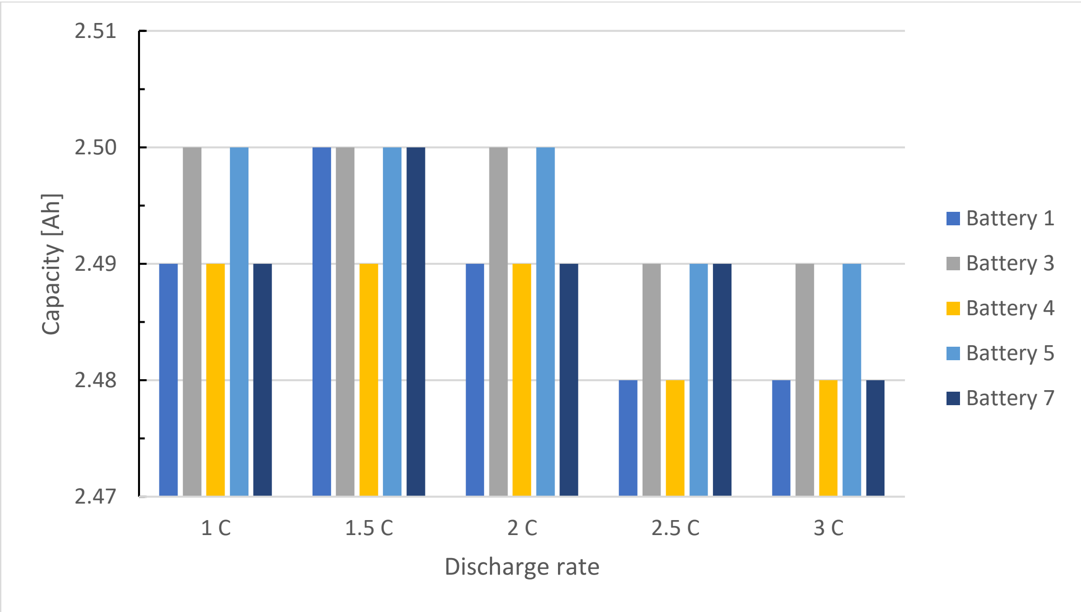
Appendix D.5: SB12V2600P-AC with a temperature sensor. The temperature sensor is fastened using strips. Between battery and sensor is thermal paste to ensure optimal contact.

Appendix E. Other results: Performance and Capacity-test

Capacity results

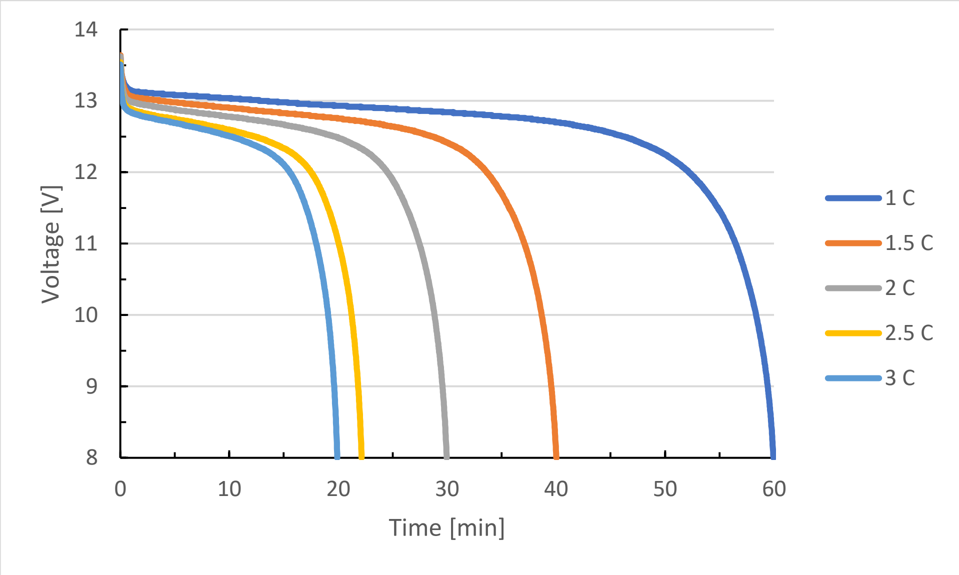


Appendix E.1: Capacity in Watt-hours for Battery 1, 3, 4, 5 and 7.

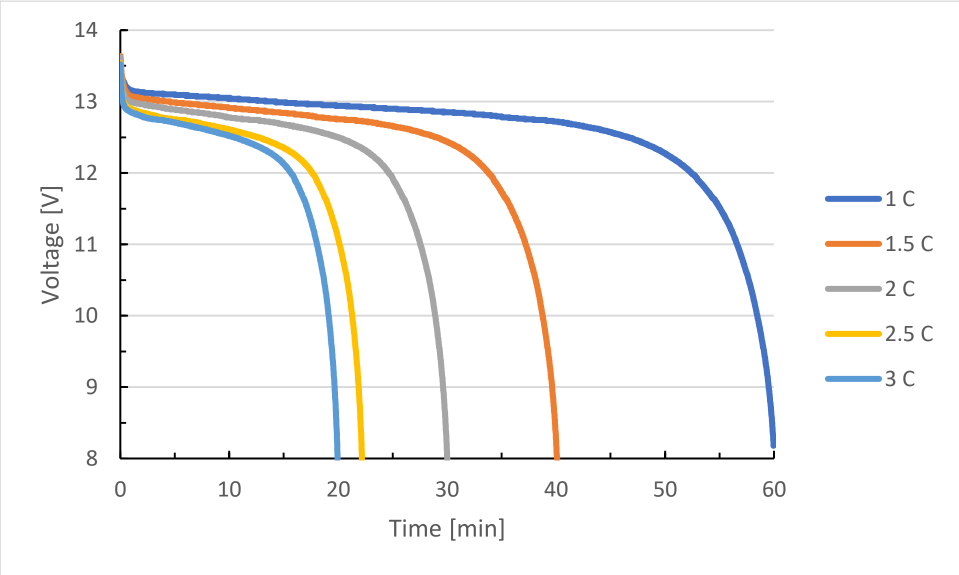


Appendix E.2: Capacity in Ampere-hours for Battery 1, 3, 4, 5 and 7.

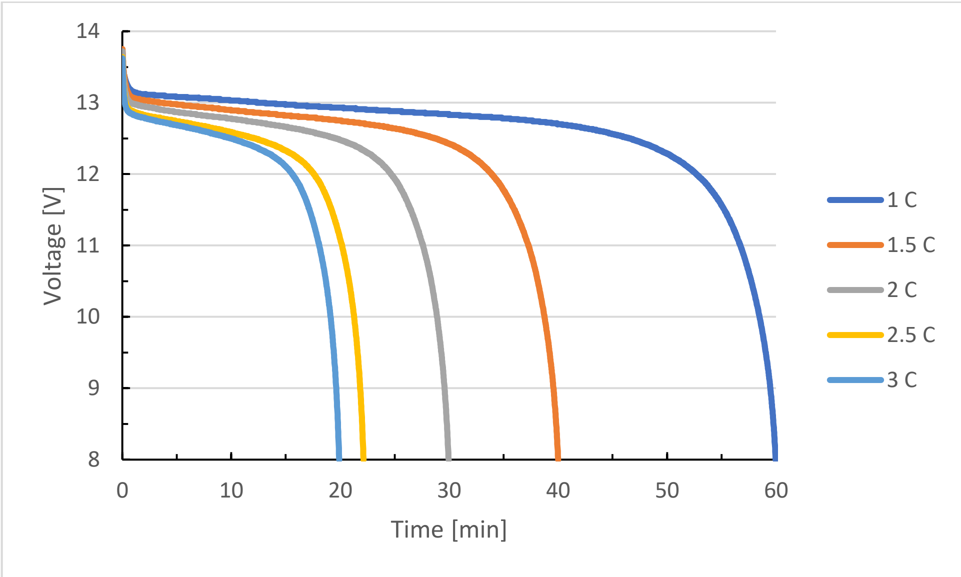
Voltage profile results



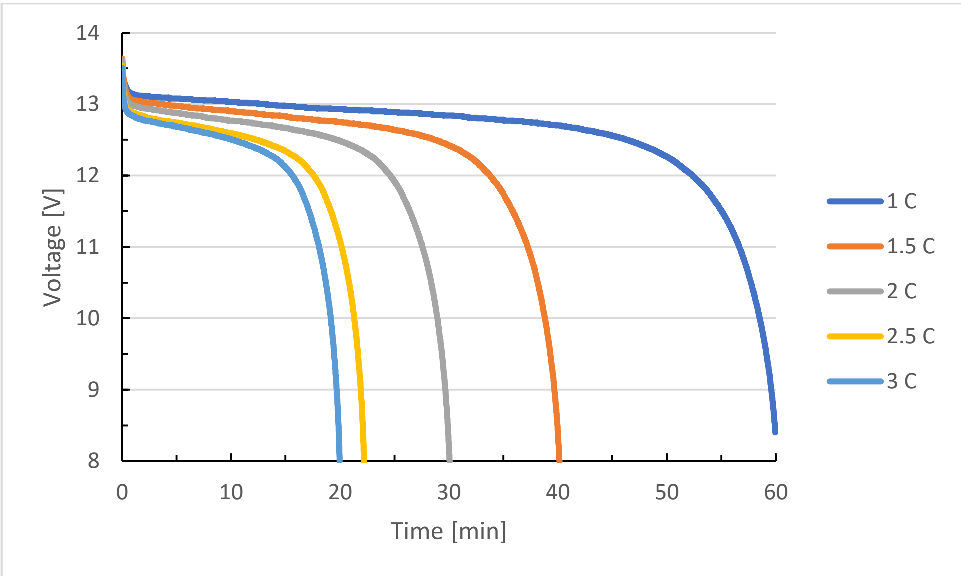
Appendix E.3: Voltage profile of Battery 2 with several discharge rates.



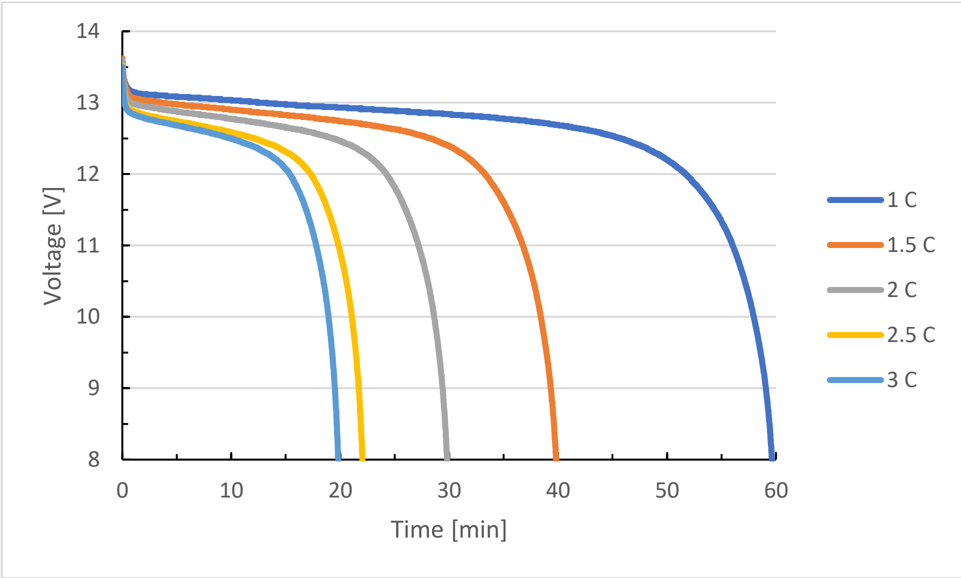
Appendix E.4: Voltage profile of Battery 3 with several discharge rates.



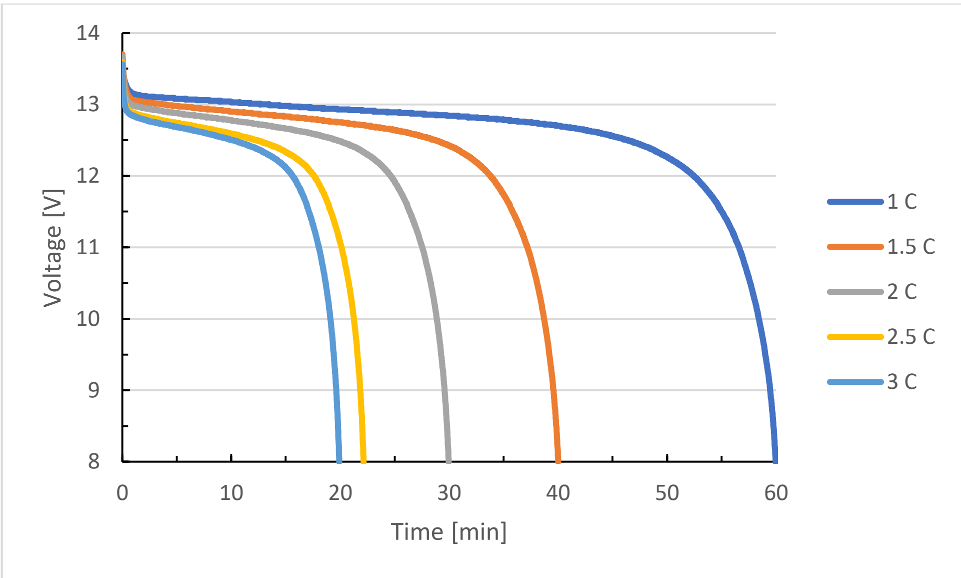
Appendix E.5: Voltage profile of Battery 4 with several discharge rates.



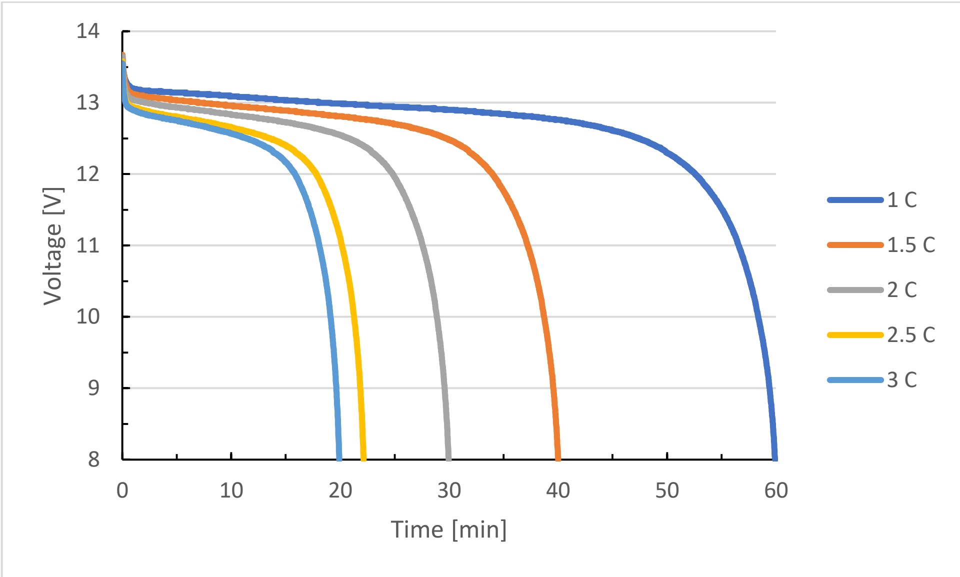
Appendix E.6: Voltage profile of Battery 5 with several discharge rates.



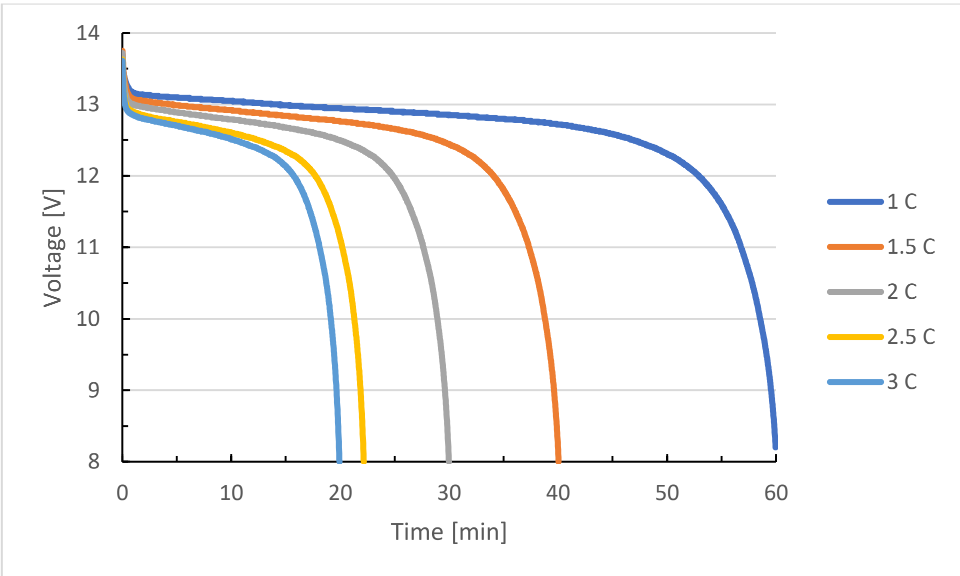
Appendix E.7: Voltage profile of Battery 6 with several discharge rates.



Appendix E.8: Voltage profile of Battery 7 with several discharge rates.

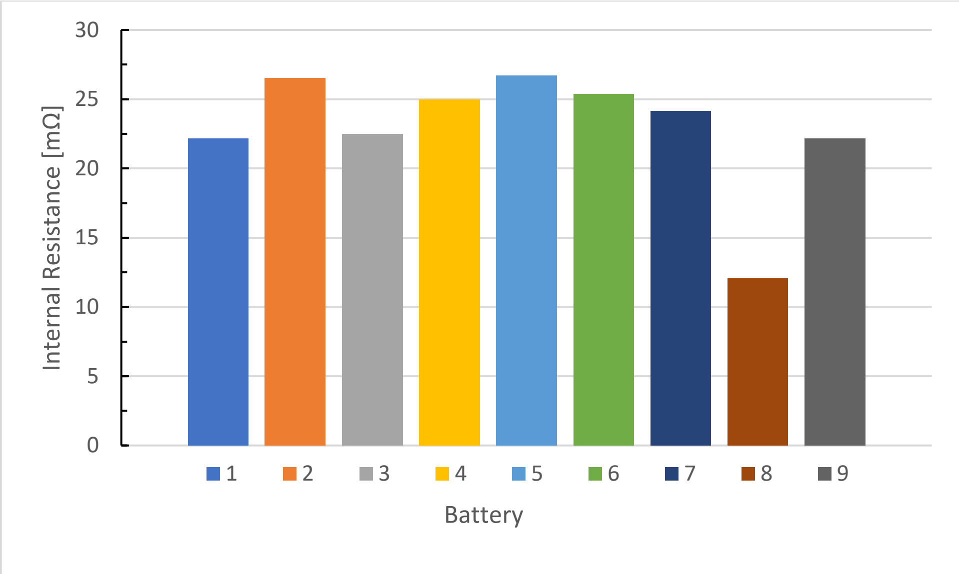


Appendix E.9: Voltage profile of Battery 8 with several discharge rates.



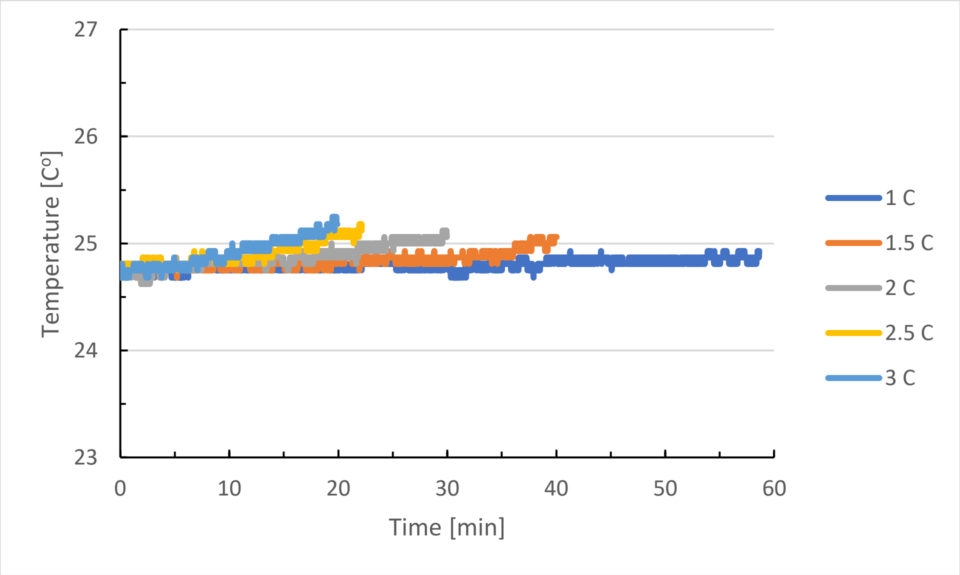
Appendix E.10: Voltage profile of Battery 9 with several discharge rates.

Internal resistance results

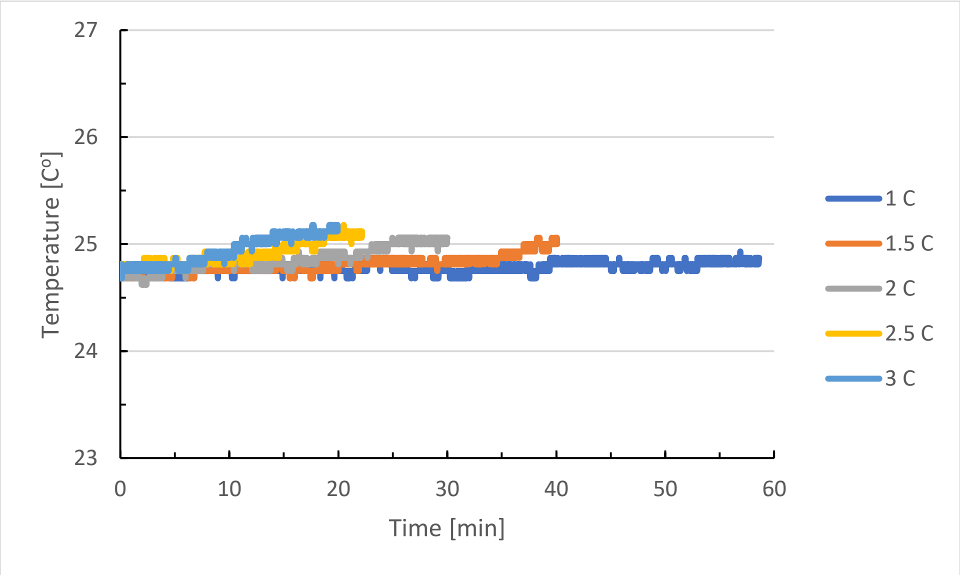


Appendix E.11: Every battery’s internal resistance during charge.

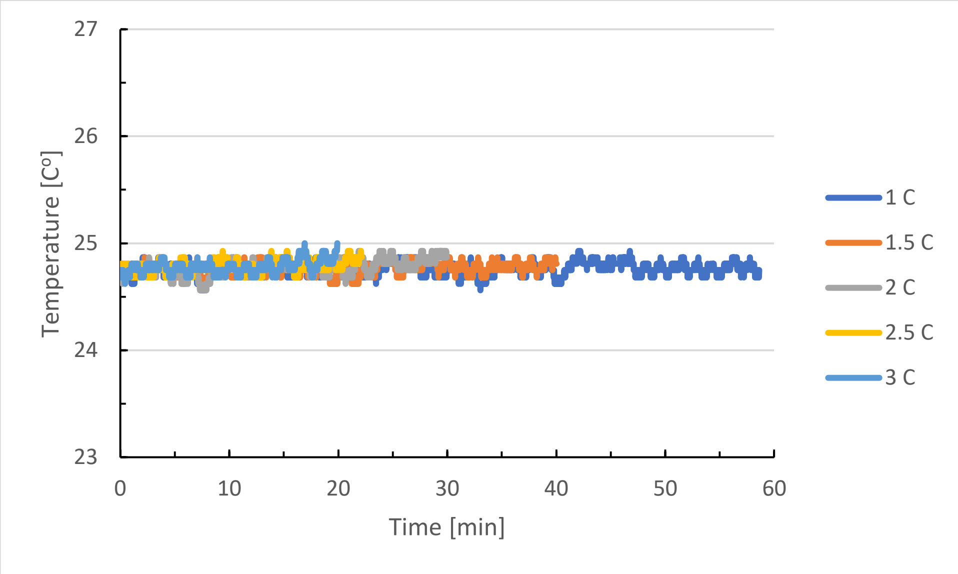
Temperature Development



Appendix E.12: Temperature development of Battery 2 with several discharge rates.



Appendix E.13: Temperature development of Battery 3 with several discharge rates.



Appendix E.14: Temperature development of Battery 4 with several discharge rates.

Appendix F. Recipes in the Recipe Editor

Performance and Capacity-test recipe

No.	Step Name	Setting			Cut-Off Condition			Jump		Loop			Cycle			Record	Description
		V(V)	I(A)	P(W)	Parameter		Value	Mode	Value	Label	Loop To	Count	Label	Cycle To	Count		
1	CC Discharge		2.5		Time(sec)	>=	7200	Next								☑	
2	CC Charge		2.5		Time(sec)	>=	7205	Next								☑	
3	DCIR Charge				T1(sec)	>=	20									☑	
4	DCIR Discharge				T1(sec)	>=	20									☑	
5	CC Charge		2,5		Time(sec)	>=	7205	Next								☑	CC Saturated C
6	CC Charge		1,25		Time(sec)	>=	7205	Next								☑	
7	CC Charge		0,6		Time(sec)	>=	7205	Next								☑	
8	CC Charge		0,3		Time(sec)	>=	7205	Next								☑	
9	CC Charge		0,125		Time(sec)	>=	7205	Next								☑	
10	REST				Time(sec)	>=	7200	Next								☑	REST
11	CC Discharge		2,5		Time(sec)	>=	7205	Next								☑	Complete discharge w
12	CC Charge		2,5		Time(sec)	>=	7205	Next								☑	CC Saturated C
13	CC Charge		1,25		Time(sec)	>=	7205	Next								☑	
14	CC Charge		0,6		Time(sec)	>=	7205	Next								☑	
15	CC Charge		0,3		Time(sec)	>=	7205	Next								☑	
16	CC Charge		0,125		Time(sec)	>=	7205	Next								☑	
17	REST				Time(sec)	>=	7200	Next								☑	REST
18	CC Discharge		3,75		Time(sec)	>=	7205	Next								☑	Complete discharge w
19	CC Charge		2,5		Time(sec)	>=	7205	Next								☑	CC Saturated C
20	CC Charge		1,25		Time(sec)	>=	7205	Next								☑	
21	CC Charge		0,6		Time(sec)	>=	7205	Next								☑	
22	CC Charge		0,3		Time(sec)	>=	7205	Next								☑	
23	CC Charge		0,125		Time(sec)	>=	7205	Next								☑	
24	REST				Time(sec)	>=	7200	Next								☑	REST
25	CC Discharge		5		Time(sec)	>=	7205	Next								☑	Complete discharge w
26	CC Charge		2,5		Time(sec)	>=	7205	Next								☑	CC Saturated C
27	CC Charge		1,25		Time(sec)	>=	7205	Next								☑	
28	CC Charge		0,6		Time(sec)	>=	7205	Next								☑	
29	CC Charge		0,3		Time(sec)	>=	7205	Next								☑	
30	CC Charge		0,125		Time(sec)	>=	7205	Next								☑	
31	REST				Time(sec)	>=	7200	Next								☑	REST
32	CC Discharge		6,75		Time(sec)	>=	7205	Next								☑	Complete discharge w
33	CC Charge		2,5		Time(sec)	>=	7205	Next								☑	CC Saturated C
34	CC Charge		1,25		Time(sec)	>=	7205	Next								☑	
35	CC Charge		0,6		Time(sec)	>=	7205	Next								☑	
36	CC Charge		0,3		Time(sec)	>=	7205	Next								☑	
37	CC Charge		0,125		Time(sec)	>=	7205	Next								☑	
38	REST				Time(sec)	>=	7200	Next								☑	REST
39	CC Discharge		7,5		Time(sec)	>=	7205	Next								☑	Complete discharge w

Appendix F.1: PC-test recipe in Recipe Editor.

Shallow Cycle-recipe

No.	Step Name	Setting V(V)	Setting I(A)	Setting P(W)	Cut-Off Condition Parameter		Cut-Off Condition Value	Jump Mode	Jump Value	Loop Label	Loop To	Loop Count	Cycle Label	Cycle To	Cycle Count	Record	Description
1	REST				Time(sec)	>=	7200	Next						b	2	☑	Rest
2	CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 60% Cap
					V(V)	>	13.533	Next									
3	DCIR Discharge				T1(sec)	>=	20									☑	DCIR Discharge
					T2(sec)	>=	20	Next									
4	DCIR Charge				T1(sec)	>=	20									☑	DCIR Charge
					T2(sec)	>=	20	Next									
5	CC Charge		2.5		Time(sec)	>=	3605	Next			a	400				☑	Charge up to 65%
					V(V)	>	13.561	Next									
6	CC Discharge		2.5		Time(sec)	>=	3605	Next		a						☑	Discharge down to 55
					W(Wh)	>	3.1755	Next									
7	CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 60% Cap
					V(V)	>	13.533	Next									
8	CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Saturation Charge
					V(V)	>	14.6	Next									
9	CC Charge		1.25		Time(sec)	>=	3605	Next								☑	Saturation Charge
					V(V)	>	14.6	Next									
10	CC Charge		0.6		Time(sec)	>=	3605	Next								☑	Saturation Charge
					V(V)	>	14.6	Next									
11	CC Charge		0.3		Time(sec)	>=	3605	Next								☑	Saturation Charge
					V(V)	>	14.6	Next									
12	CC Charge		0.125		Time(sec)	>=	3605	Next								☑	Saturation Charge
					V(V)	>	14.6	Next									
13	REST				Time(sec)	>=	7200	Next								☑	Rest
14	CC Discharge		2.5		Time(sec)	>=	7200	Next					b			☑	Complete Discharge
					V(V)	<	8	Next									

Appendix F.2: Shallow Cycle-recipe in the Recipe Editor.

Deep Cycle-recipe

No.	Step Name	Setting			Cut-Off Condition			Jump		Loop			Cycle			Record	Description
		V(V)	I(A)	P(W)	Parameter		Value	Mode	Value	Label	Loop To	Count	Label	Cycle To	Count		
1	REST				Time(sec)	>=	7200	Next						b	2	✓	Rest
2	CC Charge		2.5		Time(sec)	>=	3605	Next								✓	Charge up to 60% Cap
					V(V)	>	13.533	Next									
3	DCIR Discharge				T1(sec)	>=	20									✓	DCIR Discharge
					T2(sec)	>=	20	Next									
4	DCIR Charge				T1(sec)	>=	20									✓	DCIR Charge
					T2(sec)	>=	20	Next									
5	CC Charge		2.5		Time(sec)	>=	3605	Next			a	100				✓	Charge up to 80%
					V(V)	>	13.657	Next									
6	CC Discharge		2.5		Time(sec)	>=	3605	Next		a						✓	Discharge down to 40
					W(Wh)	>	12.702	Next									
7	CC Charge		2.5		Time(sec)	>=	3605	Next								✓	Charge up to 60% Cap
					V(V)	>	13.533	Next									
8	CC Charge		2.5		Time(sec)	>=	3605	Next								✓	Saturation Charge
					V(V)	>	14.6	Next									
9	CC Charge		1.25		Time(sec)	>=	3605	Next								✓	Saturation Charge
					V(V)	>	14.6	Next									
10	CC Charge		0.6		Time(sec)	>=	3605	Next								✓	Saturation Charge
					V(V)	>	14.6	Next									
11	CC Charge		0.3		Time(sec)	>=	3605	Next								✓	Saturation Charge
					V(V)	>	14.6	Next									
12	CC Charge		0.125		Time(sec)	>=	3605	Next								✓	Saturation Charge
					V(V)	>	14.6	Next									
13	REST				Time(sec)	>=	7200	Next								✓	Rest
14	CC Discharge		2.5		Time(sec)	>=	7200	Next					b			✓	Complete Discharge
					V(V)	<	8	Next									

Appendix F.3: Deep Cycle-recipe in the Recipe Editor.

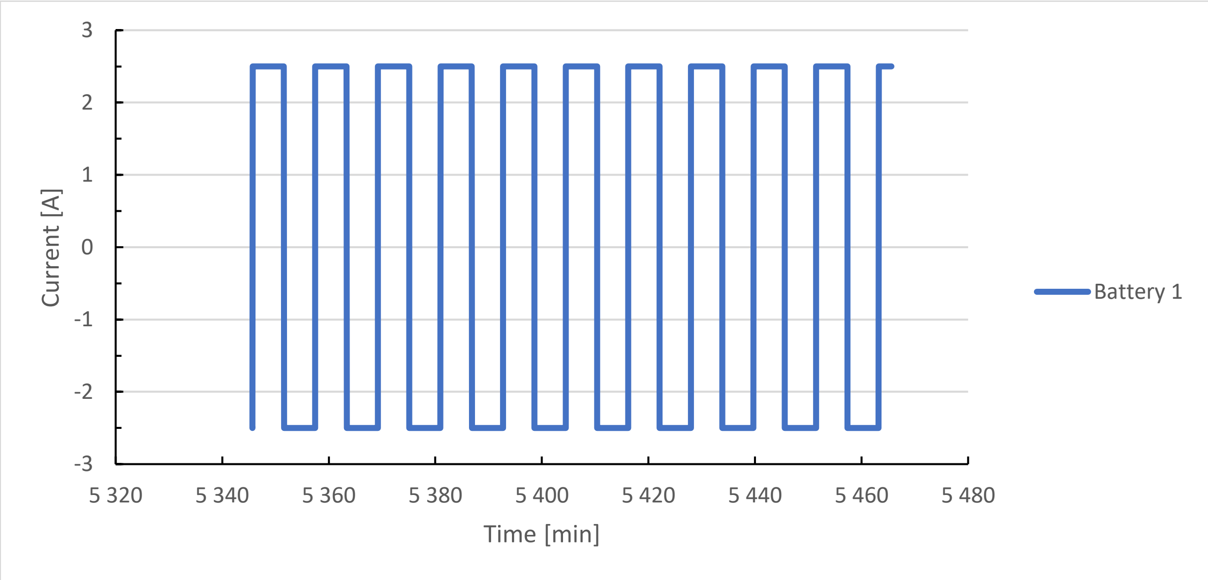
Combined Cycle-recipe

No.		Step Name	Setting			Cut-Off Condition			Jump		Loop			Cycle			Record	Description
			V(V)	I(A)	P(W)	Parameter		Value	Mode	Value	Label	Loop To	Count	Label	Cycle To	Count		
1		REST				Time(sec)	>=	7200	Next						b	2	☑	Rest
2		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 60% cap
						V(V)	>	13.533	Next									
3		DCIR Discharge				T1(sec)	>=	20									☑	DCIR Discharge
4		DCIR Charge				T1(sec)	>=	20									☑	DCIR Charge
5		CC Charge		2.5		Time(sec)	>=	3605	Next			a	40				☑	Charge up to 70%
						W(Wh)	>	3.1775	Next									
6		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 65
						W(Wh)	>	1.58875	Next									
7		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 75%
						W(Wh)	>	3.1775	Next									
8		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 70
						W(Wh)	>	1.58875	Next									
9		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 80% Cap
						V(V)	>	13.657	Next									
10		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 70
						W(Wh)	>	3.1775	Next									
11		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 75%
						W(Wh)	>	1.58875	Next									
12		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 65
						W(Wh)	>	3.1775	Next									
13		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 70%
						W(Wh)	>	1.58875	Next									
14		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 60
						W(Wh)	>	3.1775	Next									
15		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 65%
						W(Wh)	>	1.58875	Next									
16		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 55
						W(Wh)	>	3.1775	Next									
17		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 60%
						W(Wh)	>	1.58875	Next									
18		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 50
						W(Wh)	>	3.1775	Next									
19		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 55%
						W(Wh)	>	1.58875	Next									
20		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 45
						W(Wh)	>	3.1775	Next									
21		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 50%
						W(Wh)	>	1.58875	Next									
22		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 40
						W(Wh)	>	3.1775	Next									
23		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 50%
						W(Wh)	>	3.1775	Next									
24		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 45
						W(Wh)	>	1.58875	Next									
25		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 55%
						W(Wh)	>	3.1775	Next									
26		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 50
						W(Wh)	>	1.58875	Next									
27		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 60%
						W(Wh)	>	3.1775	Next									
28		CC Discharge		2.5		Time(sec)	>=	3605	Next								☑	Discharge down to 55
						W(Wh)	>	1.58875	Next									
29		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Charge up to 65%
						W(Wh)	>	3.1775	Next									
30		CC Discharge		2.5		Time(sec)	>=	3605	Next		a						☑	Discharge down to 60
						W(Wh)	>	1.58875	Next									
31		CC Charge		2.5		Time(sec)	>=	3605	Next								☑	Saturation Charge
						V(V)	>	14.6	Next									
32		CC Charge		1.25		Time(sec)	>=	3605	Next								☑	Saturation Charge
						V(V)	>	14.6	Next									
33		CC Charge		0.6		Time(sec)	>=	3605	Next								☑	Saturation Charge
						V(V)	>	14.6	Next									
34		CC Charge		0.3		Time(sec)	>=	3605	Next								☑	Saturation Charge
						V(V)	>	14.6	Next									
35		CC Charge		0.125		Time(sec)	>=	3605	Next								☑	Saturation Charge
						V(V)	>	14.6	Next									
36		REST				Time(sec)	>=	7200	Next								☑	Rest
37		CC Discharge		2.5		Time(sec)	>=	7200	Next					b			☑	Complete Discharge
						V(V)	<	8	Next									

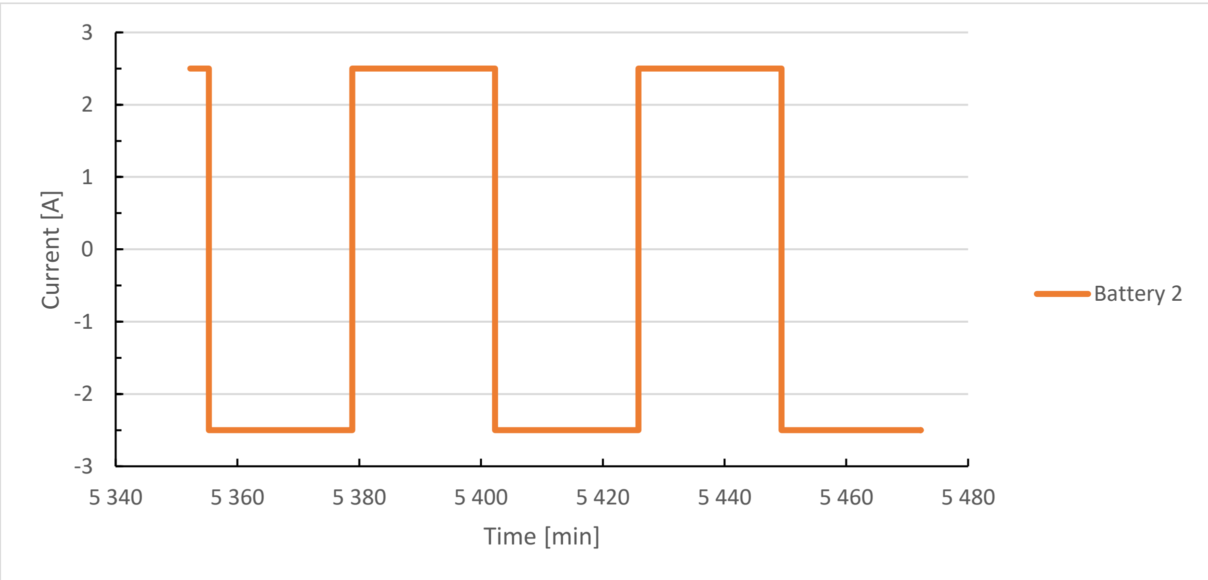
Appendix F.4: Combined Cycle-recipe in the Recipe Editor.

Appendix G. Other results: Cycle-tests

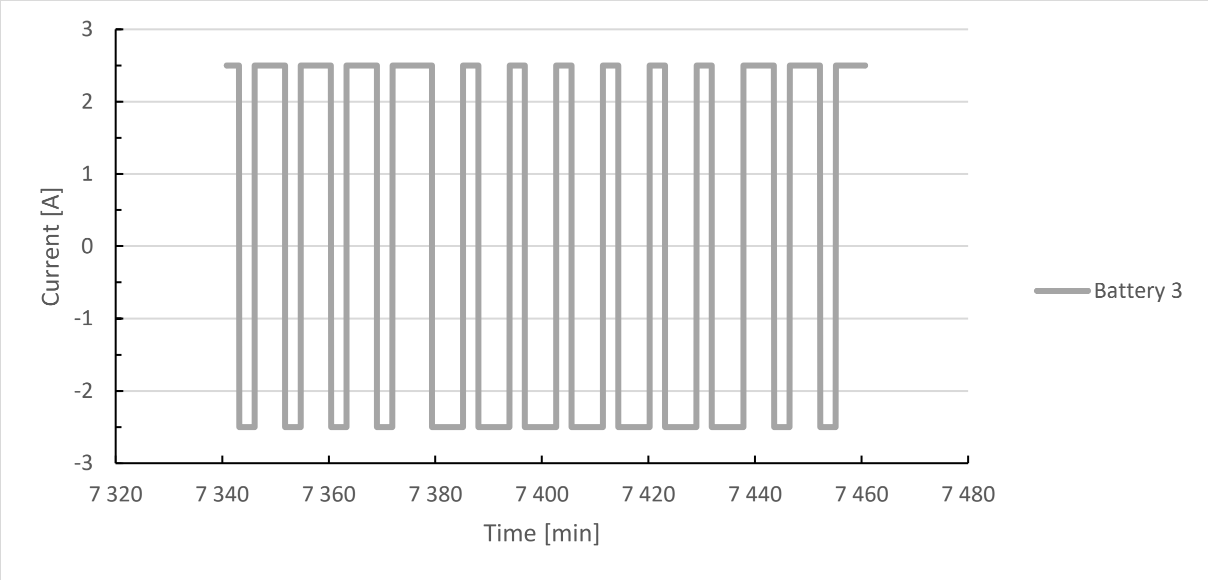
Stream of Current



Appendix G.1: Two-hour stream of current for Battery 1 at a random point during the Shallow Cycle-test.

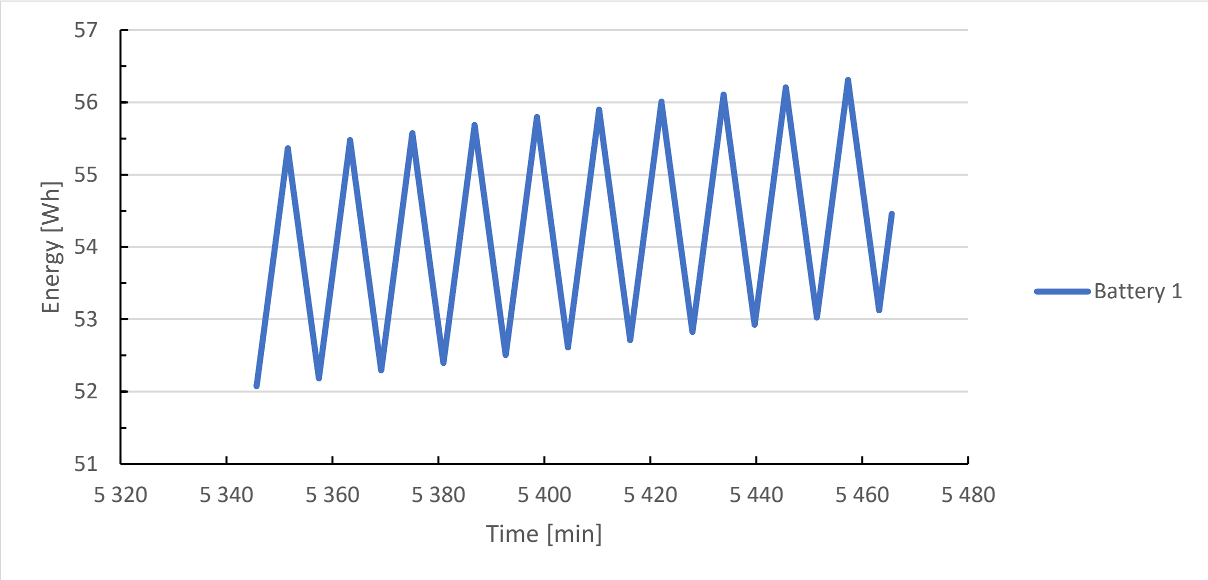


Appendix G.2: Two-hour stream of current for Battery 2 at a random point during the Deep Cycle-test.

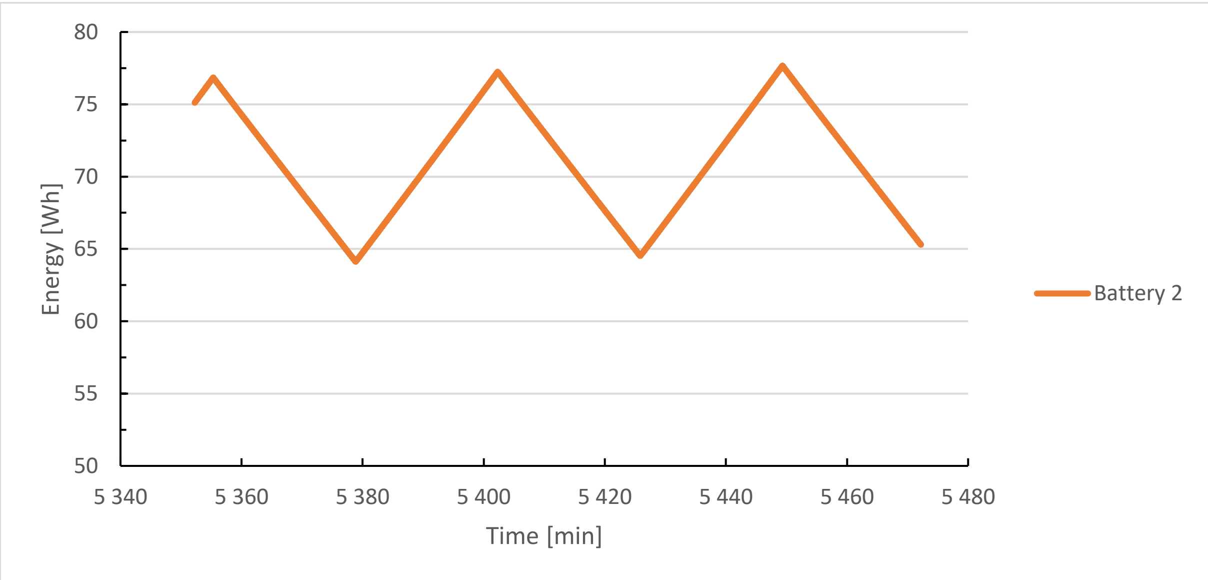


Appendix G.3: Two-hour stream of current for Battery 3 at a random point during the Combined Cycle-test.

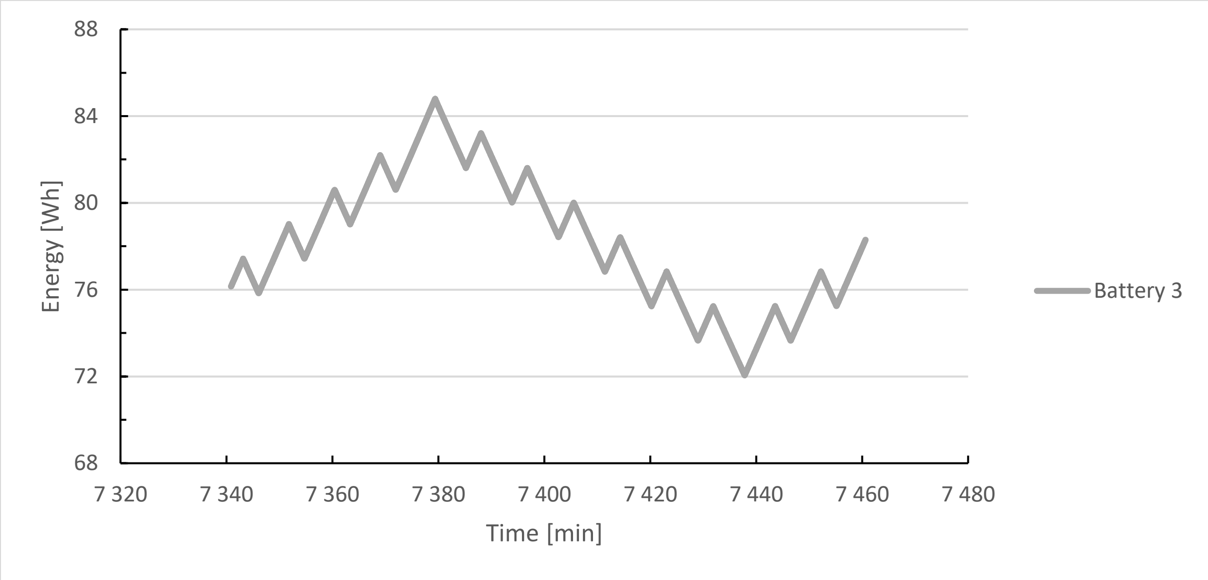
Stream of Accumulated Energy



Appendix G.4: Two-hour stream of accumulated energy for Battery 1 at a random point during the Shallow Cycle-test.

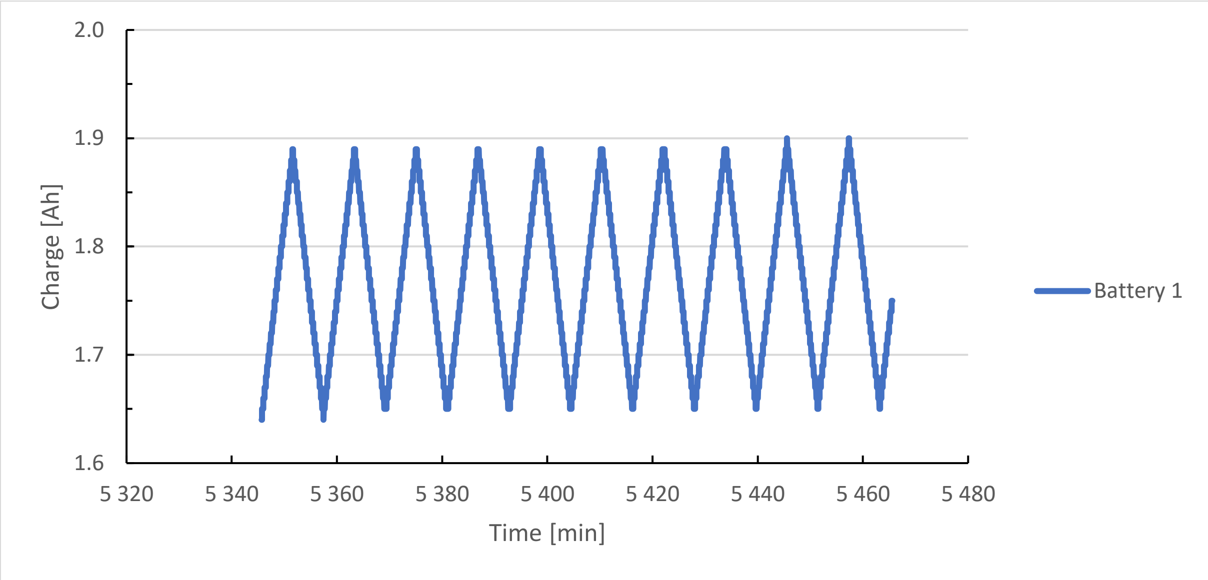


Appendix G.5: Two-hour stream of accumulated energy for Battery 2 at a random point during the Deep Cycle-test.

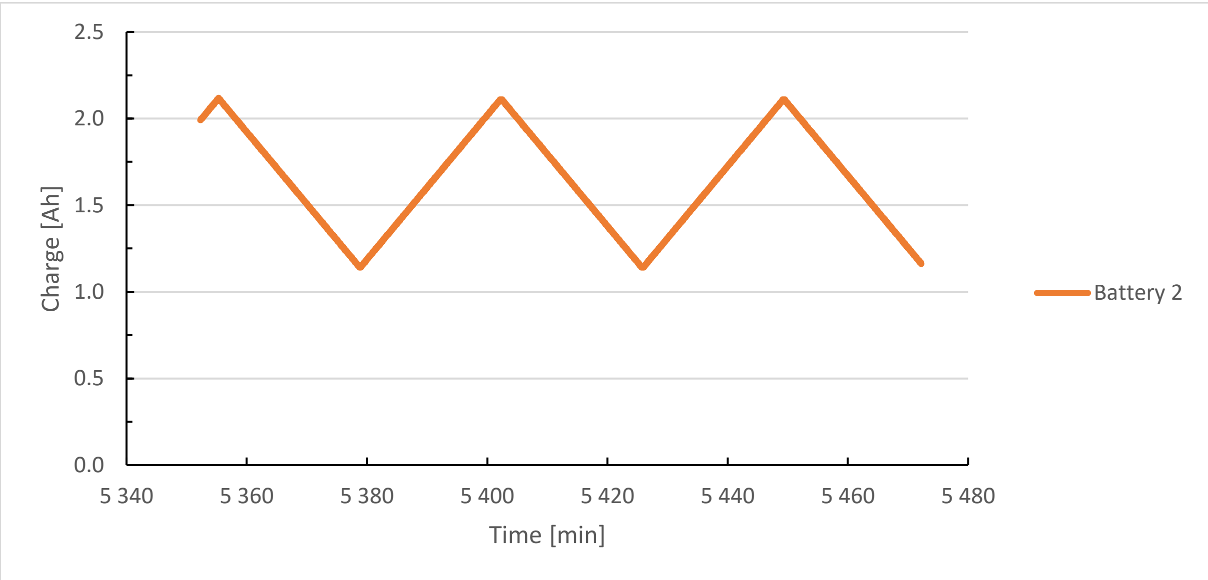


Appendix G.6: Two-hour stream of accumulated energy for Battery 3 at a random point during the Combined Cycle-test.

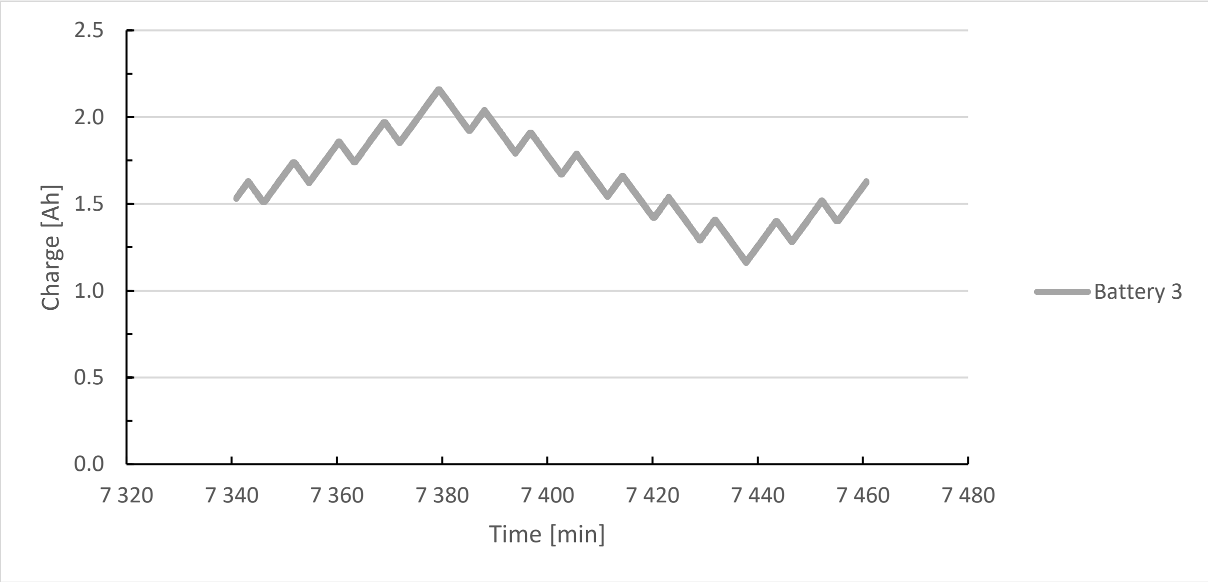
Stream of Accumulated Charge



Appendix G.7: Two-hour stream of accumulated charge for Battery 1 at a random point during the Shallow Cycle-test.

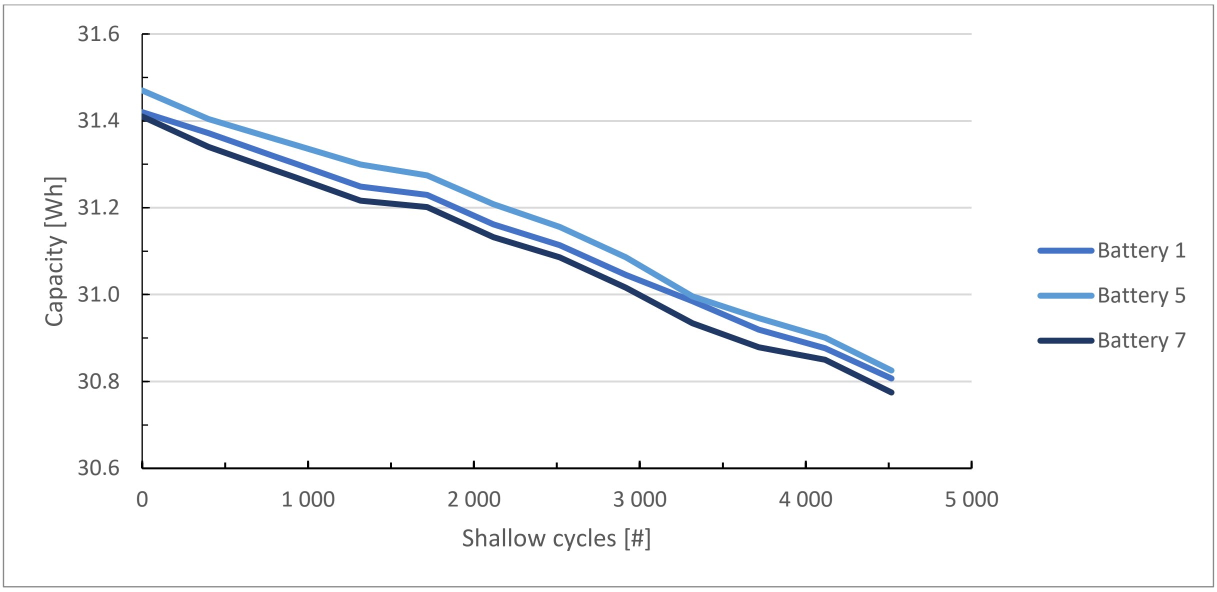


Appendix G.8: Two-hour stream of accumulated charge for Battery 2 at a random point during the Deep Cycle-test.

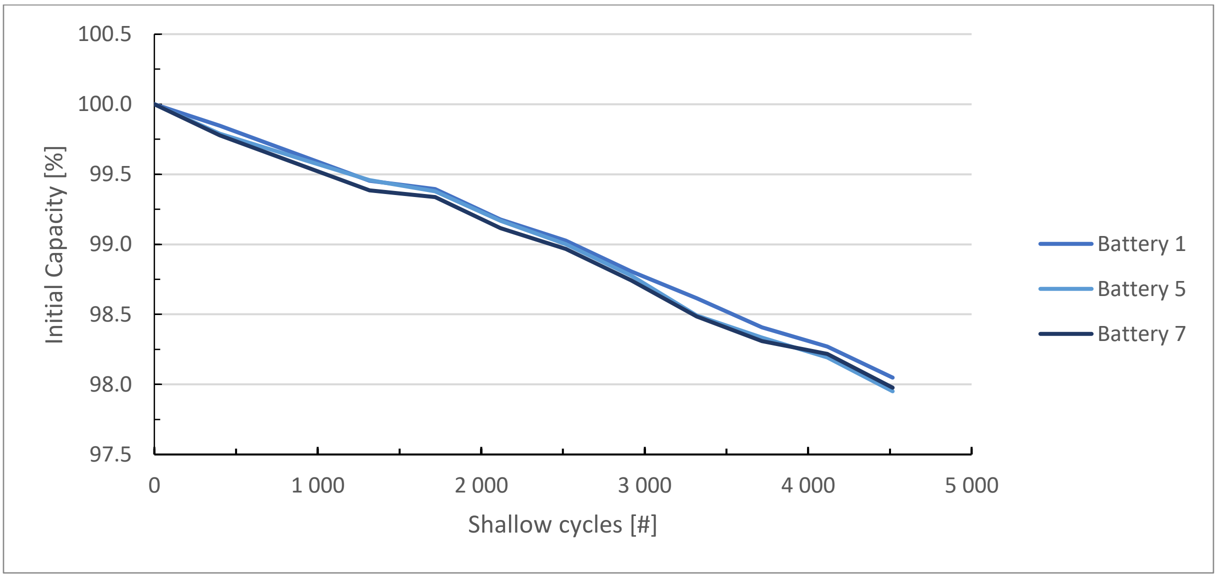


Appendix G.9: Two-hour stream of accumulated charge for Battery 3 at a random point during the Combined Cycle-test.

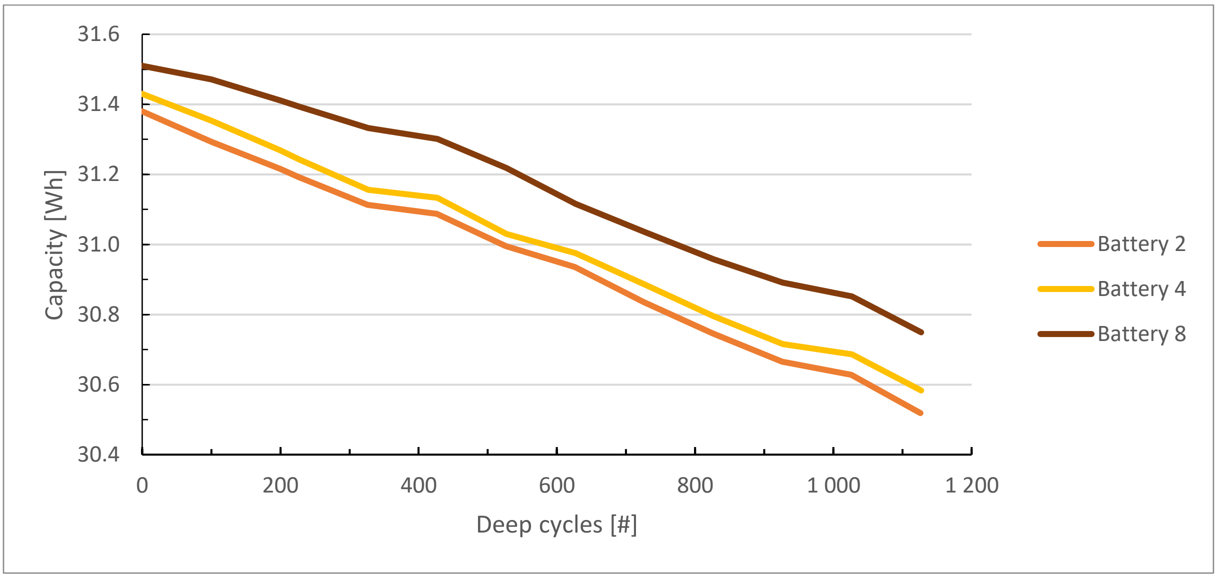
Battery capacity



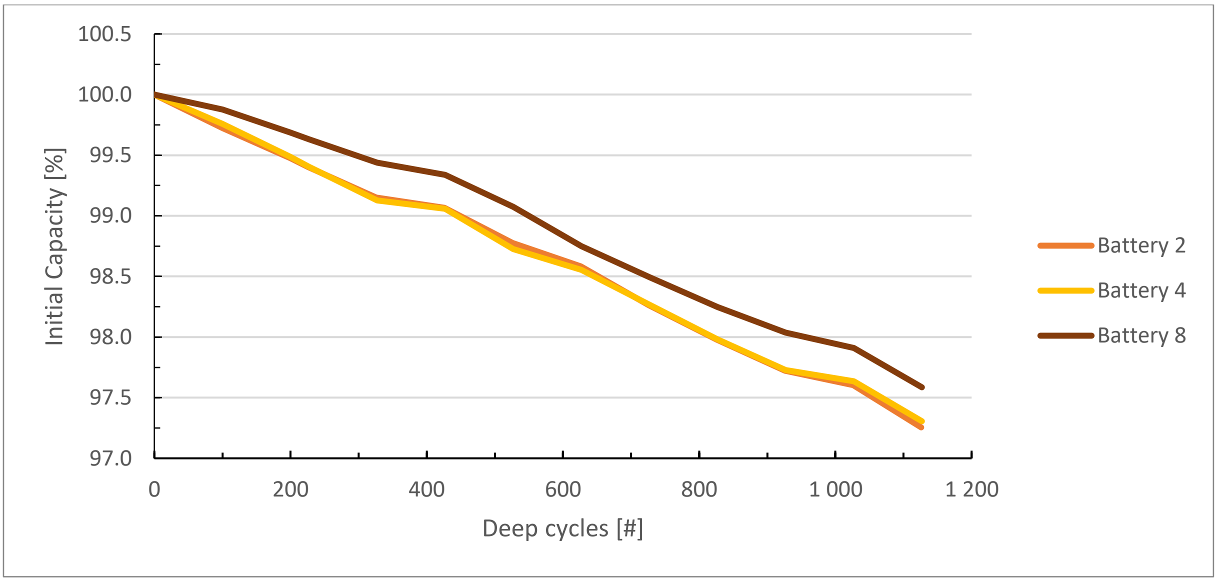
Appendix G.10: Capacity decrease for Battery 1, 5 and 7 running the Shallow Cycle-test.



Appendix G.11: Capacity decrease for Battery 1, 5 and 7 running the Shallow Cycle-test. Capacity is represented in percent calculated from the battery's initial capacity.

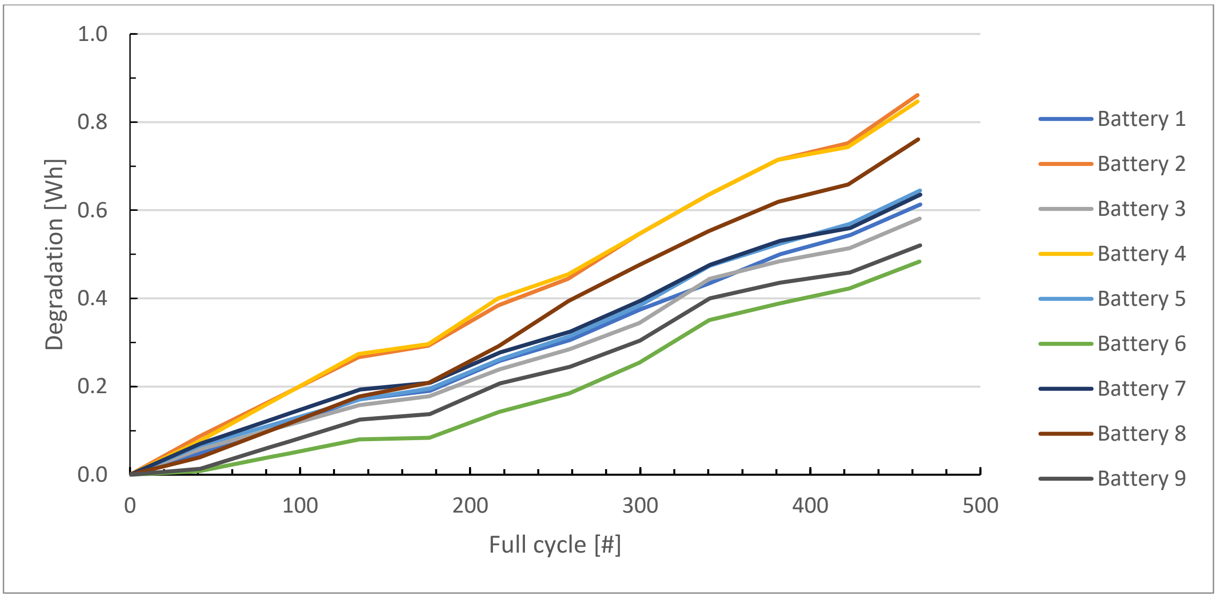


Appendix G.12: Capacity decrease for Battery 2, 4 and 8 running the Deep Cycle-test.



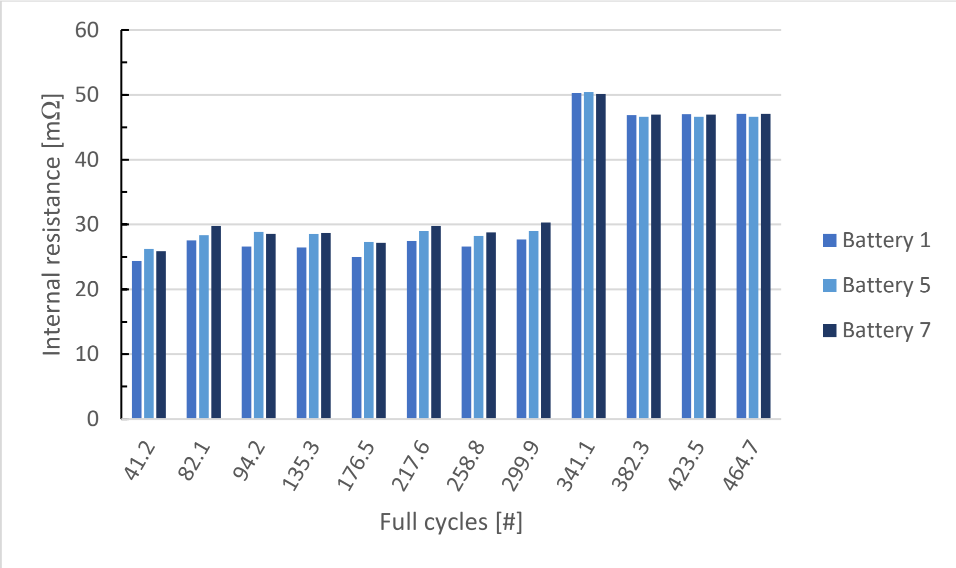
Appendix G.13: Capacity decrease for Battery 2, 4 and 8 running the Deep Cycle-test. Capacity is represented in percent calculated from the battery's initial capacity.

Battery degradation

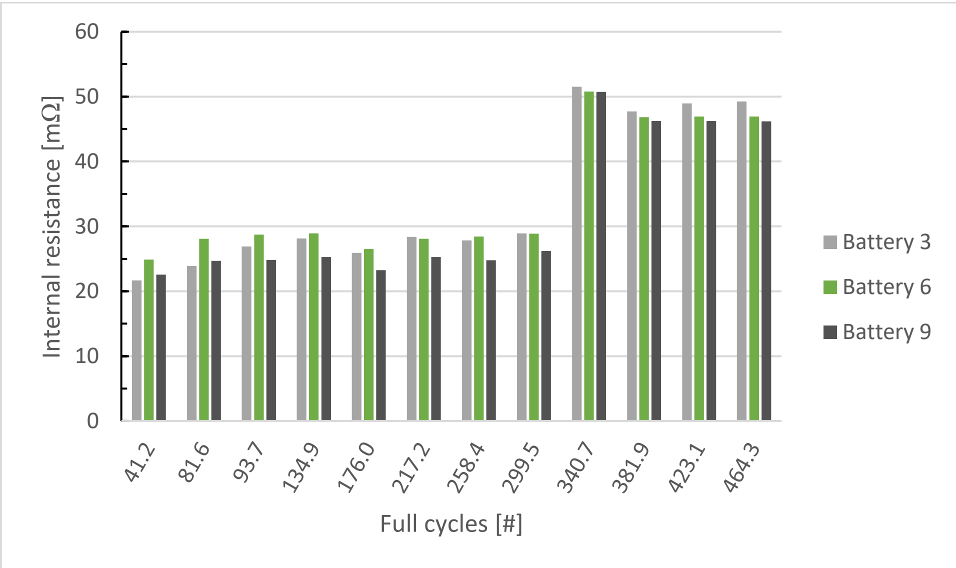


Appendix G.14: Battery degradation in Wh.

Internal resistance.

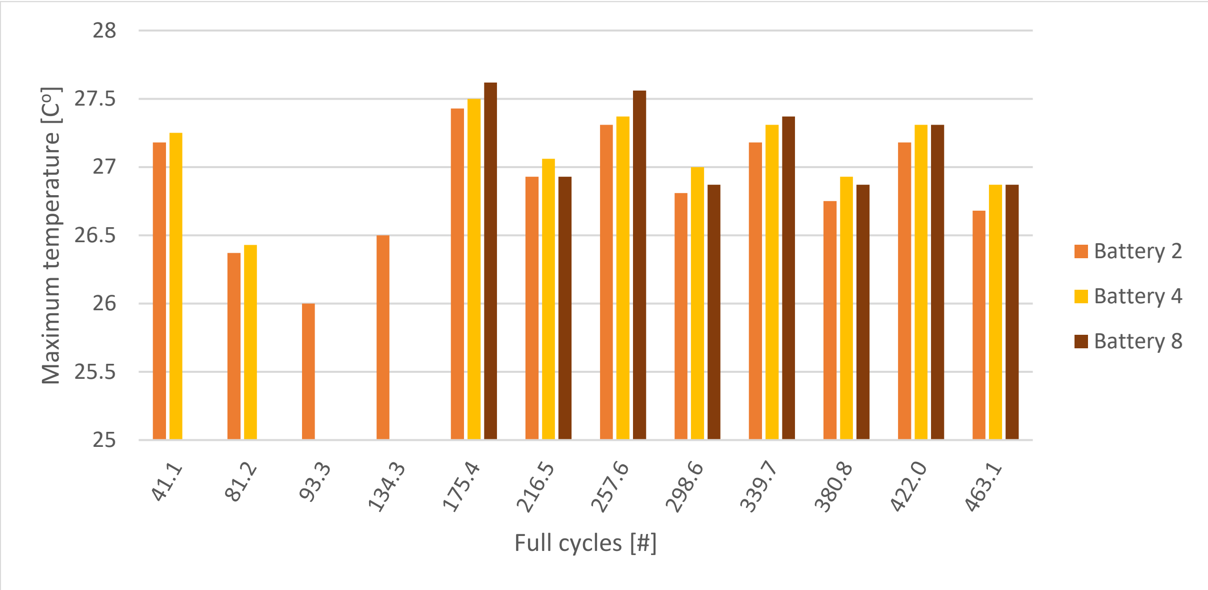


Appendix G.15: Internal resistance for Battery 1, 5, and 7 executing the Shallow Cycle-test. The values are measured during discharge. The amount of full cycles is from Battery 1. However, Battery 5 only differ with 0.2 full cycles at the last measurement.

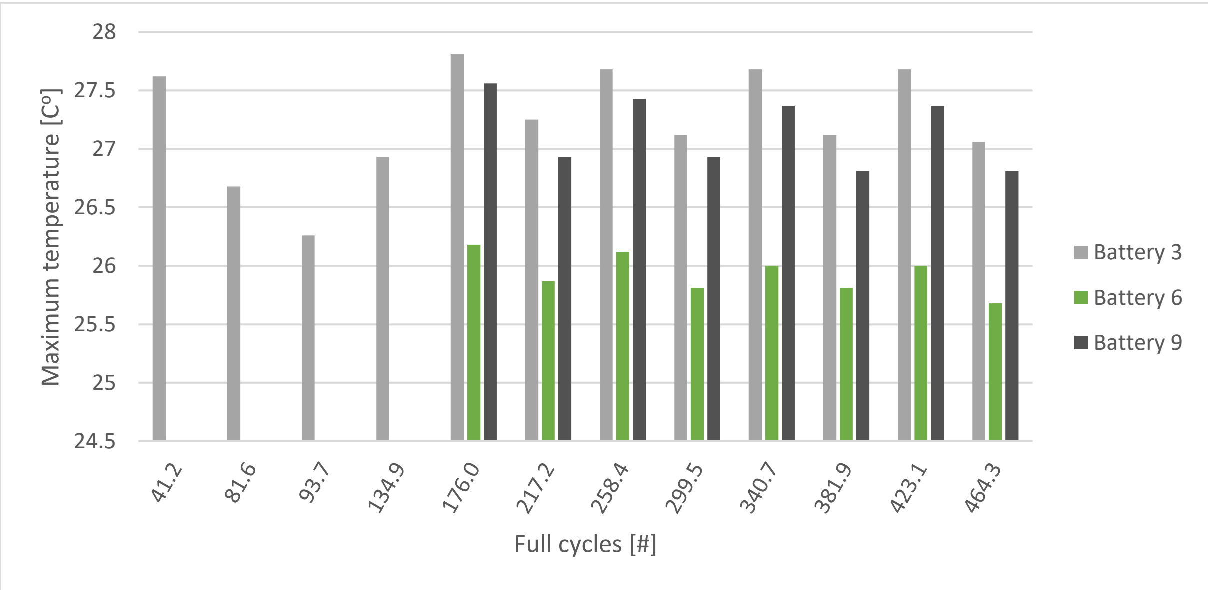


Appendix G.16: Internal resistance for Battery 3, 6, and 9 executing the Combined Cycle-test. The values are measured during discharge. The amount of full cycles is from Battery 3. However, Battery 9 only differ with 0.3 full cycles at the last measurement.

Temperature



Appendix G.17: Maximum temperature recorded after each time the Deep Cycle-test is performed for Battery 2, 4, and 8. Unfortunately, Battery 4 did not have a temperature sensor between 82- and 134 full cycles. Battery 8 did not have a temperature sensor before after 135 full cycles, which is also unfortunate.



Appendix G.18: Maximum temperature recorded after each time the Combined Cycle-test is performed for Battery 3, 6 and 9. Unfortunately, Battery 6 and 9 did not have temperature sensors the first 135 full cycles.

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An investigation of lithium-ion battery degradation during shallow-, deep-, and combined cycles

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