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BY
David HERZOG

COMPARATIVE PERFORMANCE ANALYSIS OF LI-ION AND NI-CD BATTERIES AT VARIABLE TEMPERATURES

MONTREAL, 22ND OF FEBRUARY 2016

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COMPARATIVE PERFORMANCE ANALYSIS OF LI-ION AND NI-CD BATTERIES AT VARIABLE TEMPERATURES

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RESUME

L'industrie aérospatiale recherche actuellement des solutions pour créer des avions plus légers, plus sûrs et plus puissants. L'amélioration des batteries peut aider l'industrie à atteindre ces objectifs. Dans ce rapport, les tests ont été effectués sur la technologie de batterie Ni-Cd actuellement utilisée dans l'aéronautique et sur le Li-Ion, qui est en attente d'approbation pour une utilisation en vol. Les deux technologies sont comparées. Les conditions complètes de vol ont été recréées avec un banc d'essai, pour simuler ce que la batterie va rencontrer au cours de son utilisation dans un avion. Ces batteries servent à démarrer un moteur auxiliaire (APU). Les tests ont révélé que les températures froides impactent plus les performances de la batterie que les températures chaudes, soulignant ainsi l'importance d'examiner les limites opérationnelles. L'état de charge (SOC) est le deuxième facteur le plus important réduisant les performances de la batterie. Une recommandation serait d'ajouter un système chauffant autour des batteries, pour qu'elles ne soient jamais trop froides pour effectuer un démarrage d'APU.

Mots clés: Aérospatiale, avion, batterie, Li-Ion, lithium-ion, Ni-Cad, nickel-cadmium, banc d'essai, températures variables, APU, performance

COMPARATIVE PERFORMANCE ANALYSIS OF LI-ION AND NI-CD BATTERIES AT VARIABLE TEMPERATURES

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ABSTRACT

The aerospace industry has a major focus on solutions for lighter, safer, and more powerful aircraft. Improving battery technology can advance manufacturers towards these goals. In this report, tests have been carried out on the current Ni-Cad battery technology against a new Li-Ion battery pending approval for in-flight use. Complete flight conditions were recreated with a bench test, to simulate what an aircraft battery would encounter during its service time. The batteries are utilized to start the auxiliary power unit (APU). Tests revealed that cold temperatures impact battery performance more drastically than hot temperatures, thus highlighting the importance of examining operational limits. Insufficient state of charge (SOC) has the second-greatest impact. A recommendation for the Li-Ion and Ni-Cd batteries would be to add a heating device around the battery, thus the battery will never be too cold to perform an APU start.

Keywords: aerospace, aircraft, battery, Li-Ion, lithium-ion, Ni-Cad, nickel-cadmium, bench test, variable temperatures, APU, performance

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LIST OF ABREVIATIONS

APU	Auxiliary Power Unit
ARINC	Aeronautical Radio Incorporated
BMS	Battery Management System
CC	Constant Current
CV	Constant Voltage
DOD	Depth of Discharge
Li-Ion	Lithium
Ni-Cd	Nickel-Cadmium
OCV	Open Circuit Voltage
PXI	PCI eXtensions for Instrumentation
SOC	State of charge
TDS	Test Definition Sheet
TRU	Transformer Rectifier Unit

LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

I	Battery current (A)
V	Battery voltage (V)
SOC	Battery State of Charge (%)
C	Battery capacity (Ah)
Temp	Temperature (°C)

INTRODUCTION

The first objective of this project was to set up a bench test in order to recreate the complete flight conditions the battery would encounter in an aircraft. The second objective is the analysis of the performance of a nickel-cadmium (Ni-Cad) battery compared to a lithium-ion (Li-Ion) battery. Both types of battery are utilized to start the auxiliary power unit (APU) of an airplane. Both types underwent tests at variable temperatures to observe their potential to meet the industrial customer's requirements under such conditions. By developing more reliable batteries, improvements can be made to the safety of both aircraft and electrical vehicles. The results of this paper aim to aid the industrial customer when making strategic decisions with battery choice.

Many industries, especially the aerospace industry, are currently interested in replacing aging Ni-Cad battery technology with the more recent, lighter Li-Ion technology. As Li-Ion batteries have a higher energy density compared to Ni-Cad, the overall weight of the aircraft can be reduced.

The Li-Ion batteries are equipped with a battery management system (BMS), which allows the display of the state of charge (SOC) in real time. Contrastingly, SOC of a Ni-Cad battery is not readily available in real time. The BMS also protects the cells, prevents thermal runaway, and measures the voltage, current and temperature. Because the BMS allows greater control of energy storage, Li-Ion batteries are a major interest to the aerospace industry and are currently being tested for in-flight use. The tests ensured that the battery can be used in dynamic, onboard operations in addition to stationary operations.

For use in flight, a battery must be able to deliver high currents, up to 800A, over a short period of time at temperatures between -40°C and +70°C. Extreme temperatures have the greatest impact on aircraft battery performance. Insufficient SOC has the second-greatest impact. Both of these factors contribute to the chance of starting the APU; if a battery cannot start the APU within three attempts, the aircraft will be barred from take-off. The tests in this report are designed to examine the operating range and limits of Li-Ion and Ni-Cad batteries and determine if they meet these criteria. The batteries have been tested in the following order: First the Li-Ion S1, then the Li-Ion S2, followed by the Ni-Cd and to finish the Li-Ion S2N.

CHAPTER 1

Ni-Cd AND Li-Ion GENERAL CHARACTERISTICS

1.1 Battery basic concepts

This report focuses on the Ni-Cd and Li-Ion batteries. A battery is a device that converts chemical energy into electric energy. A battery is composed of several cells. These cells can be connected in series to increase the voltage or in parallel to increase the capacity (Ah). The cells can also be connected in serial/parallel to achieve a specific voltage and current. The capacity of a battery is expressed in ampere-hour (Ah) and it represents the available energy of the battery. The charge and discharge current of a battery are measured in C-rate, e.g. for a 50Ah battery, 1C rate corresponds to 50A.

SOC

The state of charge (SOC) represents the remaining energy available in the battery, expressed in percentage. When the SOC is at 100% the battery is fully charged and at 0% the battery is empty. The depth of discharge (DOD) represents the percentage of the battery capacity that has been discharged compared to the maximum capacity.

BMS

The Li-Ion has the advantage of having a battery management system (BMS) compared to the Ni-Cd. The BMS controls the charge and discharge, optimize the performance, enhance safety and provide live data on the battery condition. The voltage of each individual cell in the battery is continuously monitored, allowing the cell to be balanced. A short-circuit protection device is embedded in the battery, to avoid any damage to the cells. The internal temperature is controlled, if the battery go over or below a threshold, the charge current will be limited or the battery will activate the protection mode by disconnecting itself. The SOC of the battery can be calculated and displayed in real time.

Specific energy

The Figure 1-1 compares the specific energy of the Ni-Cd and the Li-Ion. The Li-Ion has a higher energy density compared to the Ni-Cd. In the figure 1-1, the energy is represented as an area to show the difference in performance that a battery can have under different conditions of use.

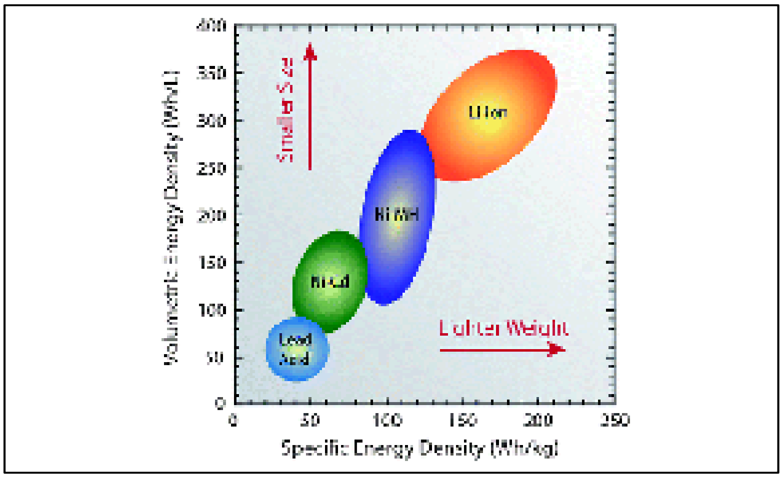

Figure 1-1 Comparison of the energy density of batteries
Taken from Landi et al. (2009, p. 640)

1.1.1 Factors affecting battery performance

Discharge rate

When there is a high discharge current, the battery voltage can drop extremely low. Therefore, the battery can be disconnected even if there is still energy inside it, because the voltage goes under the minimum threshold of the battery (cutoff voltage). Once the load is removed from the battery, the voltage slightly increase after a resting period. The capacity of the battery decreases with increasing discharge current. The service life of the battery is reduced when discharged at high current. Moreover, discharging at high rates may heat up the battery above the surrounding temperature.

Temperature

The temperature is one of the key factor affecting the battery performance. The temperature has a direct impact on the energy that the battery is able to deliver. Lowering of the discharge temperature will result in a reduction of capacity, therefore the battery will reach the cutoff voltage faster. At low temperatures, there is a reduction in chemical activity and an increase of the battery internal resistance. At high temperatures, the performance is reduced due to self-discharge or chemical deterioration. Furthermore, high temperatures accelerate the aging of the cells.

Aging and service life

There are two types of aging for a battery. The aging of the battery corresponds to a loss in energy storage capability. The first one, is related to the length of storage period, calendar life. When the battery is stored for a long time with no activity, the following parameters are affecting the battery life: the self-discharge, the temperature variations and the electrochemical system. The second one, is influenced directly by the number of cycle charge/discharge performed by the battery. The service life of the battery is specified in number of cycles. Batteries have a predetermined number of cycles before the overall capacity drops, in other words, the charge retention is reduced. Every cycle slowly reduces the battery life expectancy.

Design

The hardware used for the design of the battery will directly influence the battery performance. It will impact the thermal exchange, size and weight of the battery. These components are, for example, container material, spacing between the cells, electrical circuits, insulation and protection devices.

1.2 Test results from the literature

1.2.1 Temperature

The graphs 1-2 and 1-3 show the impact of the temperature on lithium iron phosphate (LiFePO4) cells from Lishen Co. LTD. As show in the charts 1-2 and 1-3, when the temperature is between 10°C and 40°C, the impact of temperature on the charge/discharge is not that important. However, at 0°C, the performances start to be reduced and then at -15°C the performance of the cells is significantly reduced. The 25°C curve can be used as a reference. In can be seen that during the discharge, the voltage drops rapidly with the decrease in temperature and for the charge, the voltage rises rapidly with decreasing temperature.

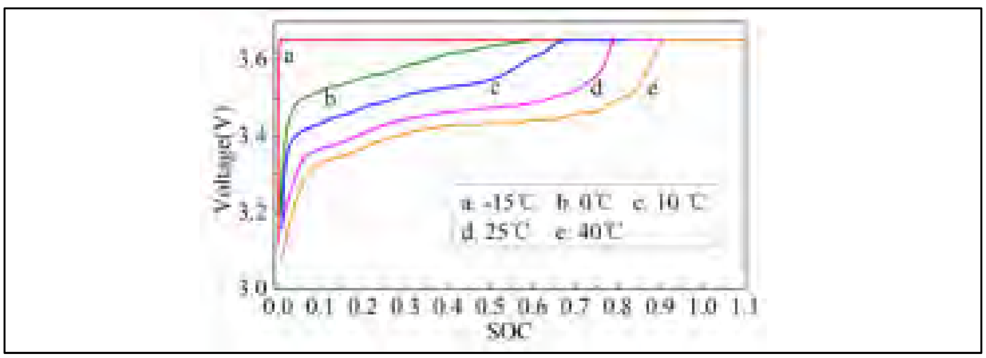

Figure 1-2 CCCV charge curves of a LiFePO4 cell at various temperatures
Taken from Li Yong et al. (2014, p. 2)

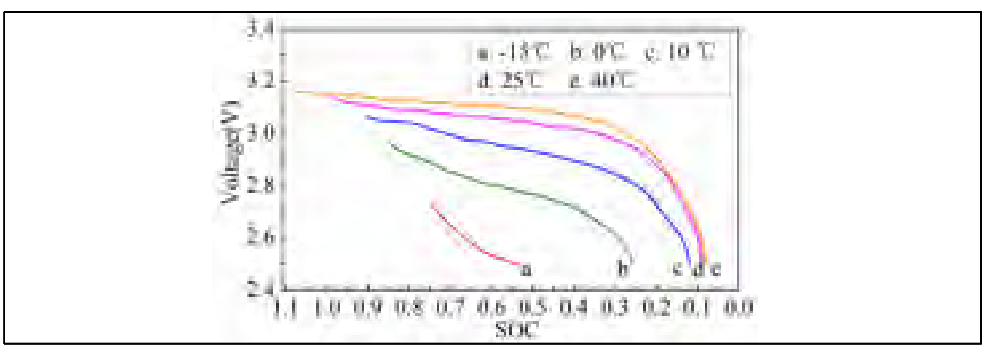

Figure 1-3 C-rate discharge curves of a LiFePO4 cell at various temperatures

Taken from Li Yong et al. (2014, p. 2)

The graph 1-4 puts into perspective the charge and discharge capacity of a LiFePO4 cell at various temperatures. At -15°C, the useable energy of the cell is at 22.2% and at 25°C it's at 91.7%, showing again the impact of temperature on the cells performance. At 40°C, the SOC is exceeding 100%. "These phenomena are due to the change of both polarization and inner resistance at different temperatures" Li Yong et al. (2014, p. 2).

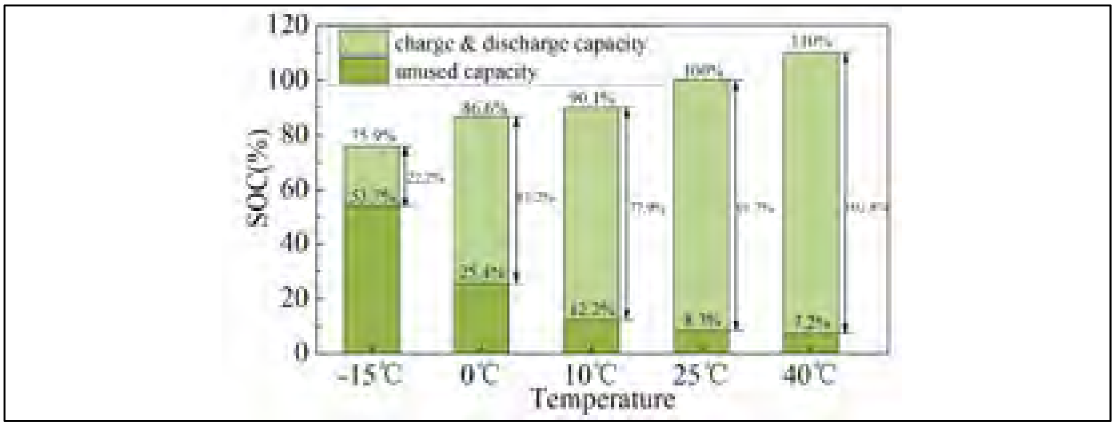

Figure 1-4 Charge and discharge capacity of a LiFePO4 cell at various temperatures
Taken from Li Yong et al. (2014, p. 2)

The high temperatures have less effect on the Li-Ion cells performance (Saft UHP VL5U). As shown in the graph 1-5, the performance remain relatively similar regardless of the discharge rate.

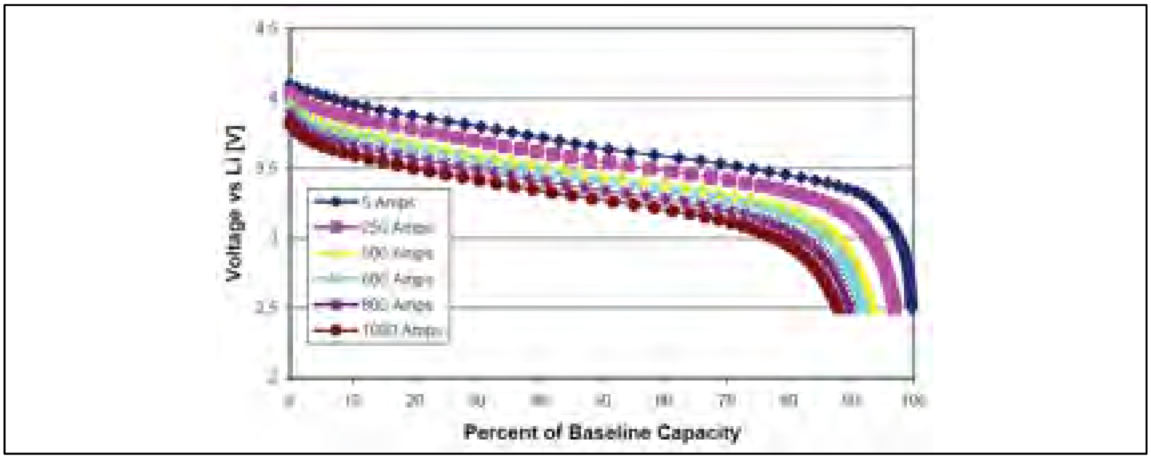

Figure 1-5 Discharge capacity at 60°C as a function of discharge rate. Saft Li-Ion cells Taken from Allen et al. (2009, p. 8)

The chart 1-6 is here to showcase the influence of the cells self-heating on the cells temperature and voltage. In this case, two Li-Ion cells wired in series have been used, no battery pack around. At the beginning of the test at -40°C, discharged at 1000A (200C), there is a drop in the voltage from 8.1V to 4.5V. Then the phenomenon is observed, the cells start to self-heat, therefore their temperature rises, increasing at the same time the voltage of the cells. Reaching a voltage of 5.11V around the middle of the discharge sequence, before sloping back down, since the battery is starting to run out of energy. The difference with the tests carried out in this thesis on the Ni-Cd and the Li-Ion batteries is, the current peaks at 800A only last for a few seconds to conduct the APU starts, compared to the chart 1-6 where the cells are discharged at 1000A until they run out of energy. This means, the Ni-Cd and the Li-Ion batteries do not have the time to self-heat as described below, since their current peaks only last for a few seconds. However, the effects of this phenomenon needs to be known in order to better understand the behaviour of the battery voltage.

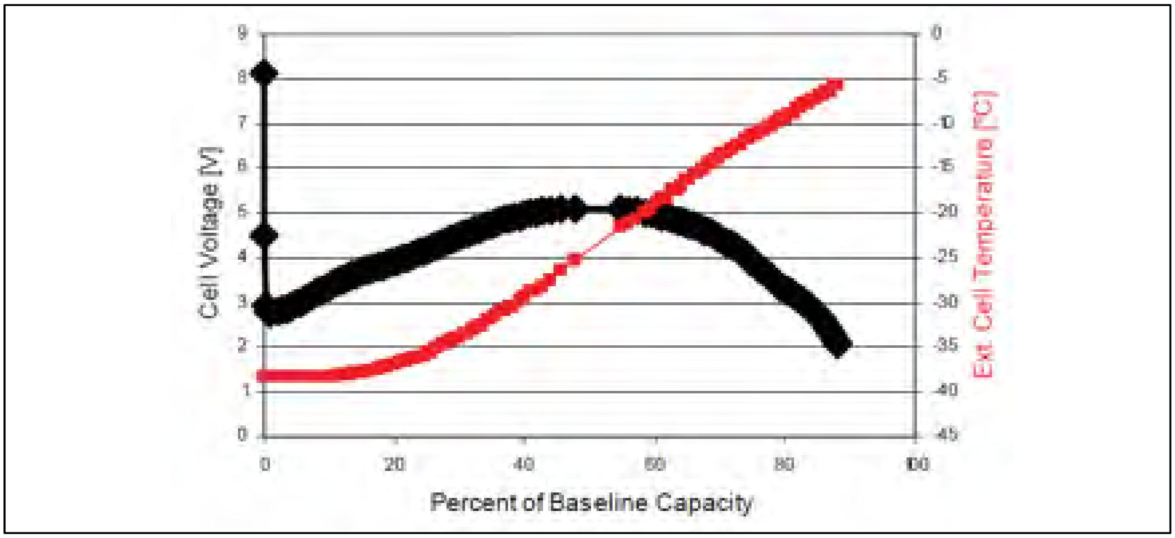

Figure 1-6 Discharge curve of two cells in series at –40°C and 1000A (200C). The black curve is voltage and the red curve is exterior cell temperature. Cells: Saft UHP (VL5U) Taken from Allen et al. (2009, p. 6)

The graph 1-7 is presented here, since the test used equivalent temperature conditions and battery capacity compared to tests carried out in this thesis. The battery is a 50Ah lithium-ion phosphate. The graph 1-7 shows the impact of the temperature on the battery performance during discharge. Starting from 0°C and lower, the battery performances are really limited. At -40°C, the battery is unable to work. The battery was discharged at constant currents of 50A (1C) and the cutoff voltage was 2.5V.

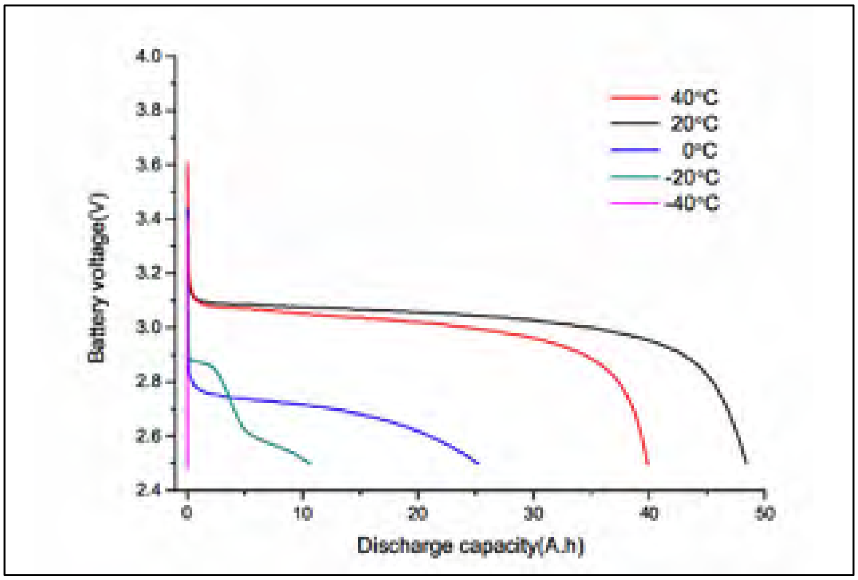

Figure 1-7 Discharging curves of 50A (1C) constant current
under different temperatures
Taken from Zang et al. (2014, p. 2)

1.2.2 Discharge rate

Another test on Li-Ion cells have been made on Saft Ultra High Power (VL5U), ratted at ~5Ah and ~20Wh. These cells were subjected to high rate discharge, up to 1000A (200C). The graph 1-8 displays the discharge capacity of a single cell at 20°C with different currents. The higher the current withdrawn, the lower the voltage. The baseline capacity is 5A. “The cell is able to deliver about 75% of the 1C (5A) discharge capacity while discharging at the 200C (1000A) rate” Allen et al. (2009, p. 3).

The same report also shows that at 1000A discharge current, the battery can deliver an energy of 36 Wh/kg and a power of 8.7 kW/kg while at 5A discharge current, the battery has an energy of 57 Wh/kg and a power of 0.052 kW/kg.

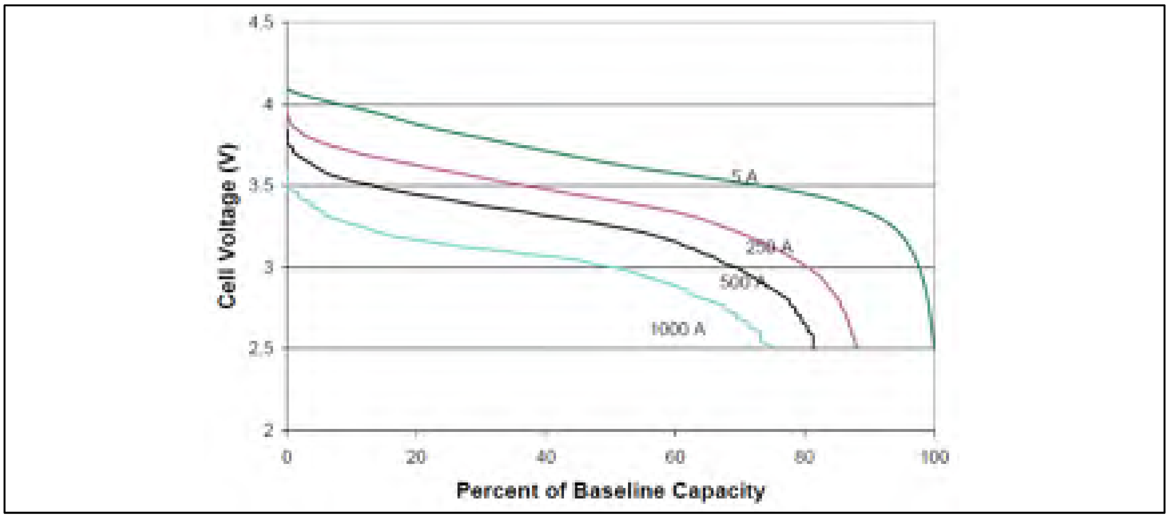

Figure 1-8 Voltage and discharge capacity as a function of rate of discharge at 20 °C
The baseline capacity is ~5 Ah at room temperature
Taken from Allen et al. (2009, p. 3)

The report concludes as following regarding the temperature and the discharge rate: “Cycling at different conditions suggests that high rate cycling degrades the cell faster than high temperature cycling, which implies that significant self-heating occurs at high rates of discharge.” Allen et al. (2009, p. 14).

1.2.3 Internal resistance

For the following statement, a 50Ah lithium-ion phosphate battery has been used. “The lower the temperature is, the greater the resistance is. Meanwhile, the increase of resistance is obvious when the temperature is below O°C, which is much more obvious for temperature under -20°C” Mengyan Zang et al. (2014, p. 8). On the other hand, the SOC shows less effect on the ohmic resistance of the battery. The battery charge resistance is significantly higher than discharge resistance, this difference is increased at temperatures below 0°C, as shown in the two charts 1-9 and 1-10.

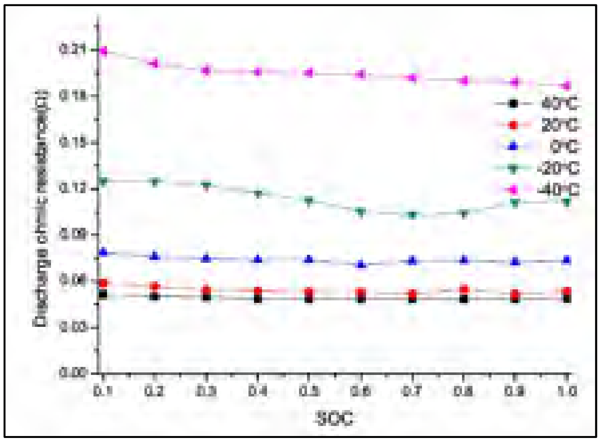

Figure 1-9 Ohmic resistance curves of discharge under different SOC and temperatures
Taken from Zang et al. (2014, p. 4)

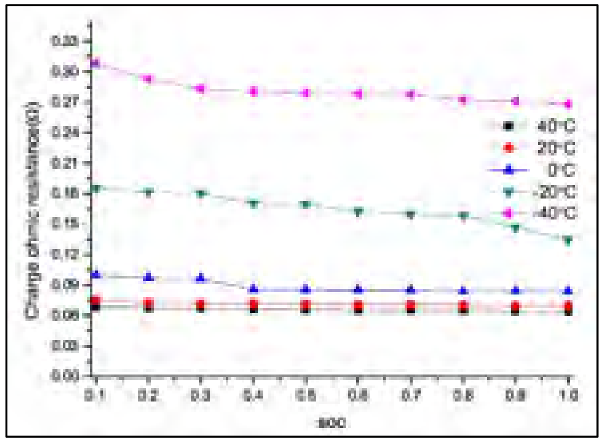

Figure 1-10 Ohmic resistance curves of charge under different SOC and temperatures
Taken from Zang et al. (2014, p. 4)

CHAPTER 2

REQUIREMENTS FOR THE TEST

2.1 The purpose of the project

The purpose of this project was to study the performance of the Li-Ion and Ni-Cd batteries designed for the aerospace industry, to assess their abilities to meet all the requirements from the test definition sheet (TDS) emitted by the aircraft manufacturer. The Li-Ion and Ni-Cd batteries are tested at different temperatures and different SOC. The batteries have been tested in the following order: First the Li-Ion S1, then the Li-Ion S2, followed by the Ni-Cd and to finish the Li-Ion S2N. Complete flight conditions were recreated to simulate what an aircraft battery would encounter during its service time. To recreate these conditions a bench test has been built.

2.2 Test Definition Sheet

The test definition sheet (TDS) has been emitted by the aircraft manufacturer. Complete flight conditions were recreated with an environmental chamber to simulate what an aircraft battery would encounter during its service time.

The flight tests are composed of two parts:

- Ground step: the aircraft (battery) stays on the ground for 20 minutes or 10 hours at a designated temperature. The 10h period is named cold soak and the 20min period is named time on ground between flights. At the end of the ground phase, three APU starts are performed. The APU starts are presented later in the report.
- Flight step: during this sequence the aircraft (battery) is surrounded by temperature of -56°C for 10 hours (long flight), 3.48 hours (medium flight) or 1.6 hours (short flight).

The figure 2.1 shows a typical profile of medium-haul flight. At the beginning, the battery is on the ground at a designated temperature. Then, the aircraft takes off to reach the cruising altitude, at this moment the battery is surrounded by a temperature of -56°C. To finish, the aircraft (battery) is landing at a new destination, with a new surrounding temperature.

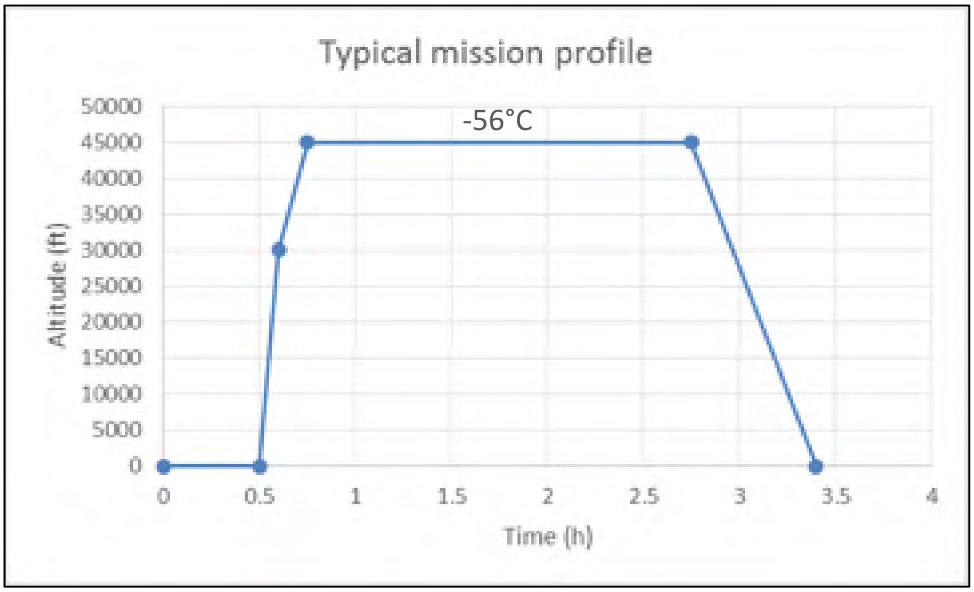

Figure 2-1 Medium-haul flight mission profile

At the beginning of each test, a specific temperature and SOC level are chosen according to the requirements from the TDS. The temperature is ranging from -40°C to +70°C and the SOC from 40% to 90%. The different temperatures in use are -40°C, -20°C, 0°C, 20°C, 30°C, 50°C and 70°C. The different SOC for the tests are 40%, 70%, 80% and 90%. This report will present the influence of the temperature and the SOC on the performances of the battery, by analysing its behaviour and limits.

2.2.1 Algorithm for the batteries tests

The following flowchart, figure 2-2, explains the normal mode process of a test on the batteries.

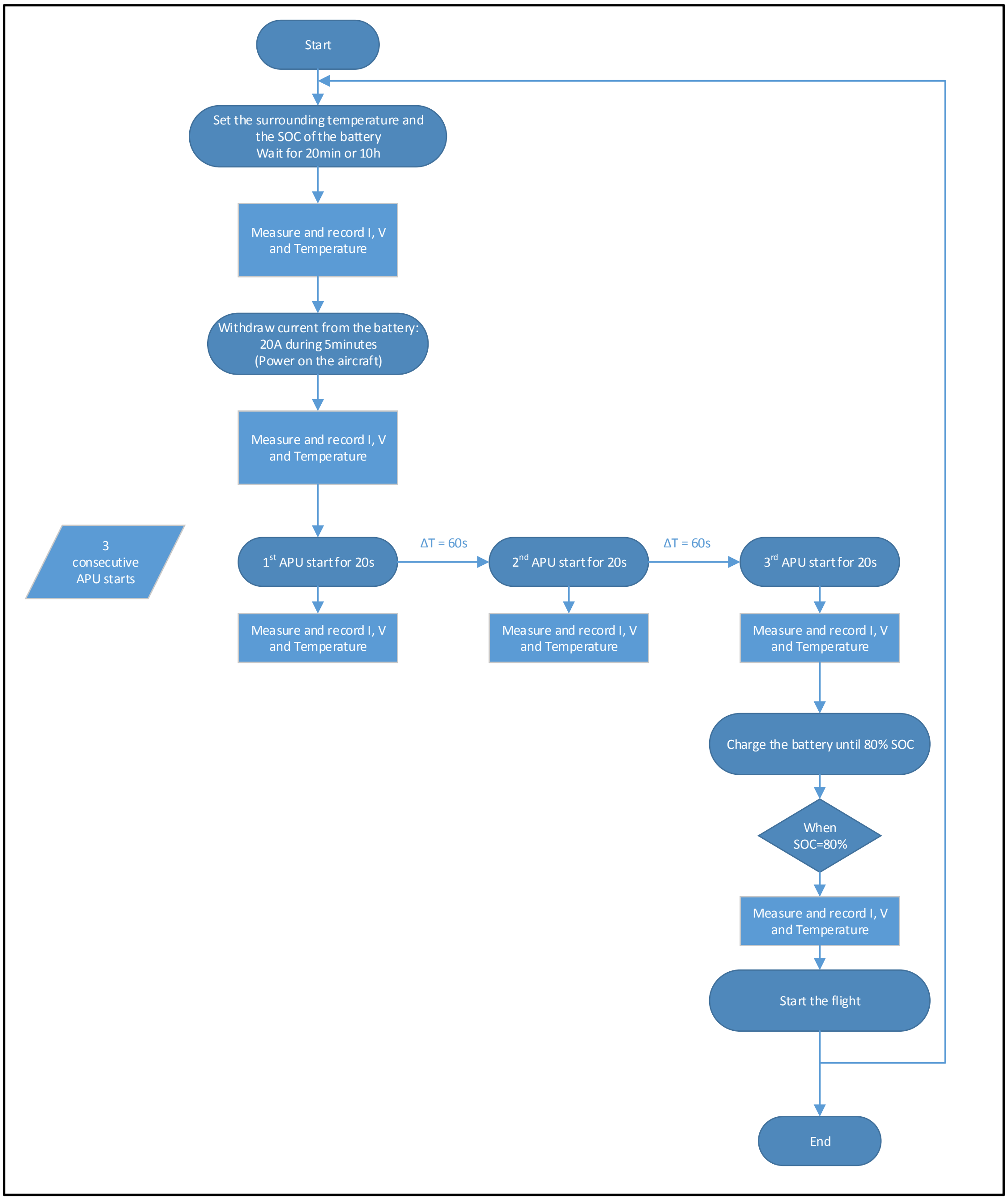

Figure 2-2 Algorithm of a flight simulation (Process to test the battery)

2.2.2 Conditions for a successful APU start

Two different APU start curves have been used. The Li-Ion S1, Li-Ion S2 and Ni-Cd batteries used the model based on the DC starter motor. The Li-Ion S2N used the model based on the Starter generator.

The following conditions only apply to the S1, S2 and Ni-Cd batteries. For an APU start to be considered successful it has to meet the following criteria:

- Minimum voltage at the battery connector: 12V;
- Inrush current: minimum 500A and maximum 1100A.

The following conditions only apply to the Li-Ion S2N battery. For an APU start to be considered successful it has to meet the following criteria:

- Minimum voltage at the battery connector: 17V;
- Inrush current: minimum 200A and maximum 500A.

2.2.3 APU start curves with DC starter motor

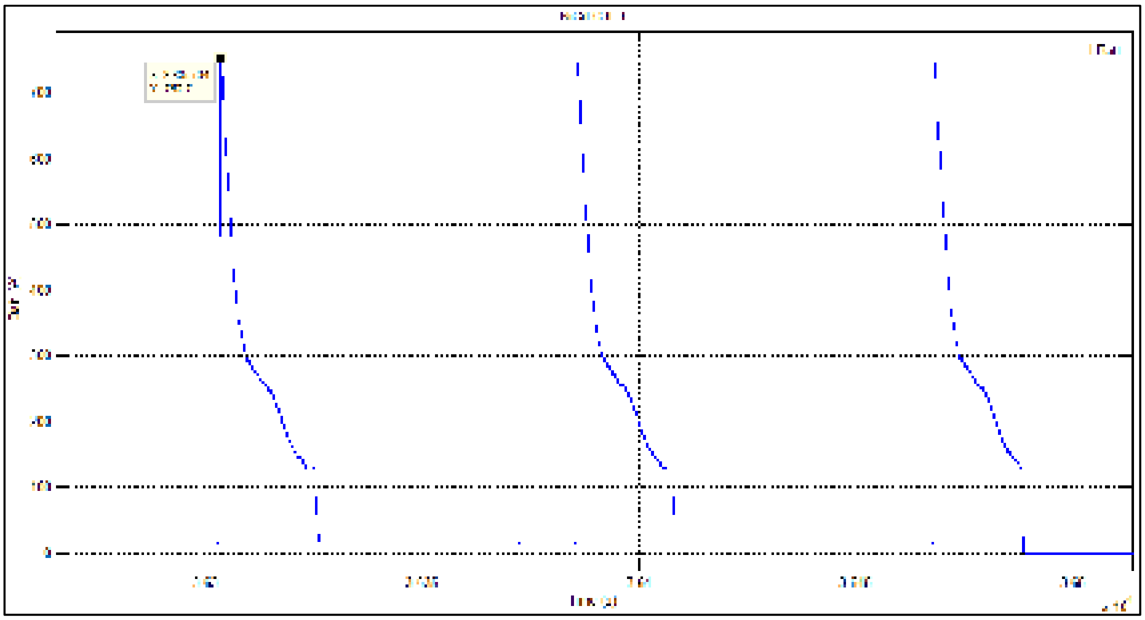

Figure 2-3 APU start current curve for S1, S2 and Ni-Cd batteries (DC starter motor)

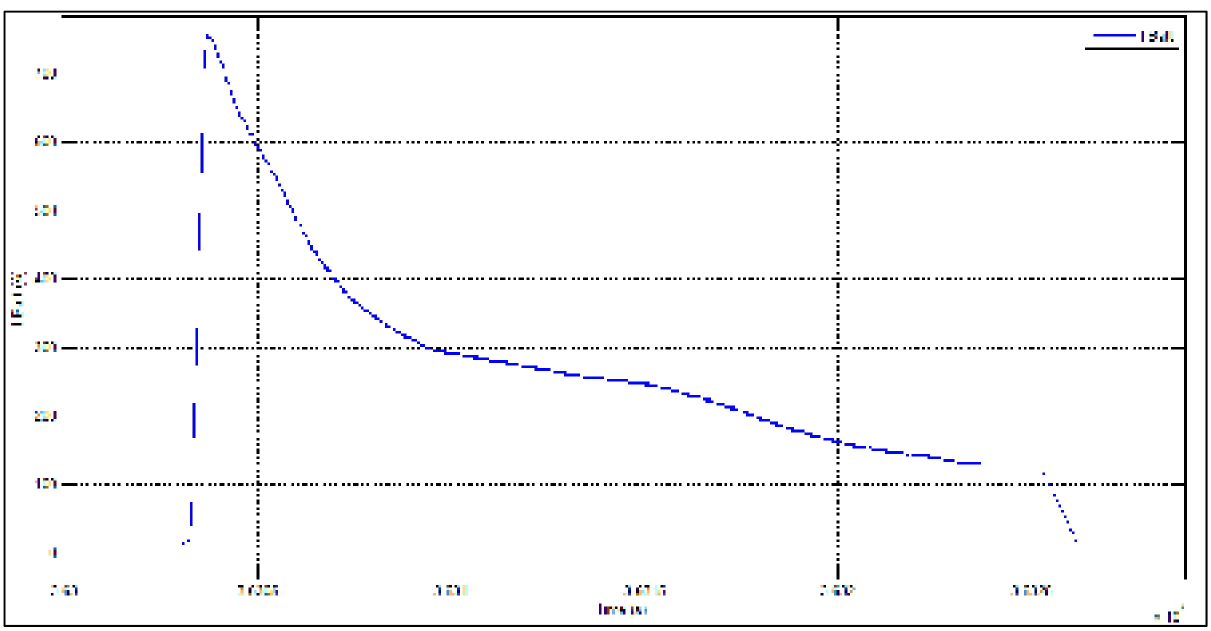

Figure 2-4 Zoom-in APU start current curve for S1, S2 and Ni-Cd batteries

2.2.4 APU start curves with Starter Generator

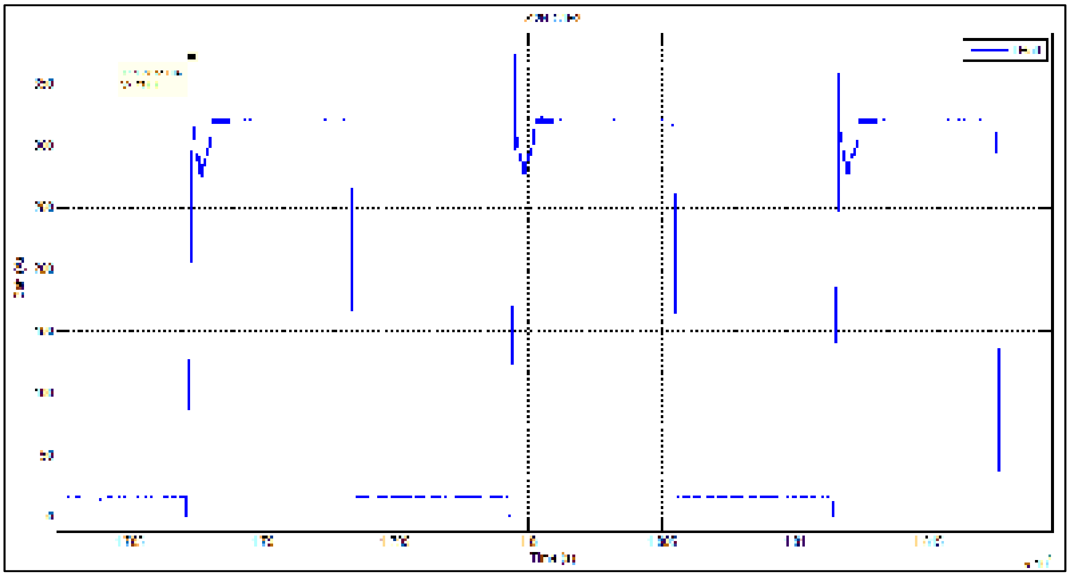

Figure 2-5 APU start current curve in use for S2N battery (Starter Generator)

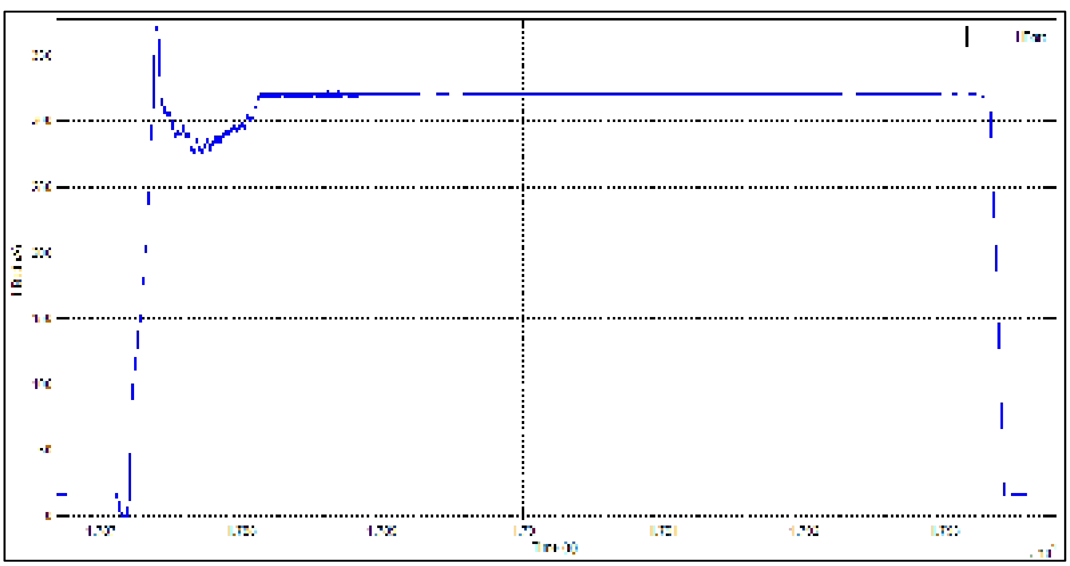

Figure 2-6 Zoom-in APU start current curve in use for S2N battery

The differences with the previous APU curve used for the S1, S2 and Ni-Cd batteries are a lower current peak at the beginning with an APU lasting longer. The APU start is now lasting

60s for the S2N battery. The APU max current is now 376A instead of the previous 750-800A.

2.3 Batteries characteristics

Presentation of the batteries characteristics and differences.

2.3.1 Batteries characteristics comparison

Table 2-1 Batteries characteristics (Source: Manufacturer user manual)

Definition	Ni-Cd	Li-Ion
Rated capacity at 1-hour rate	43Ah	45Ah
Nominal Voltage	24V	25V
Operating Temperature	-40°C to +70°C	-15°C to +71°C
Weight	38.4kg (84.7lb)	30.2kg (66lb)
Height	262.1mm (10.325in)	336mm
Width	305.5mm (12.03in)	350mm
Length	268.4mm (10.57in)	339mm

2.3.2 Technical differences between Li-Ion and Ni-Cd

The following sentences will explain the major differences between the Li-Ion and the Ni-Cd, it is not an in-depth review of the differences. The Li-Ion is equipped with a BMS (Battery Management System), one of its features, is to know in real time its SOC (State of Charge). The Li-Ion has also a higher energy density compared to the Ni-Cd, implying lighter weight for the same embedded energy. On the other hand, the decades long use of the Ni-Cd battery, still currently in use, shows its reliability as a technology.

The data available in the table 2-1 shows that the Li-Ion is 8kg lighter than the Ni-Cd. Despite the higher energy density of the Li-Ion, the fact that it has to add the BMS on the top of the cells, makes the Li-Ion battery bigger than the Ni-Cd battery. The data also show a smaller temperature operating range for the Li-Ion compared to the Ni-Cd.

2.4 Bench test

To recreate the conditions the battery will encounter during its service time, a bench test has been built.

This bench test is composed of:

1) Battery,
2) Monitoring software (LabVIEW). During the APU starts, the data are recorded at a frequency of 4kHz and during the regular phases at 1Hz;
3) Environmental test chamber: creates the surrounding temperatures that the batteries will encounter inside the aircraft, ranging from -56°C to 70°C (Thermotron XSE-600-15-15);
4) Data acquisition system: this computer allows the measure, control and save the data from the tests (NI PXI 1078);
5) TRU (Transformer Rectifier Unit): used to recharge the battery ;
6) Programmable DC load: used to simulate the APU start of the aircraft (AMREL PLW24K 120-1500);
7) Several current, voltage and temperature sensors to know the exact values at every important points of the bench test.

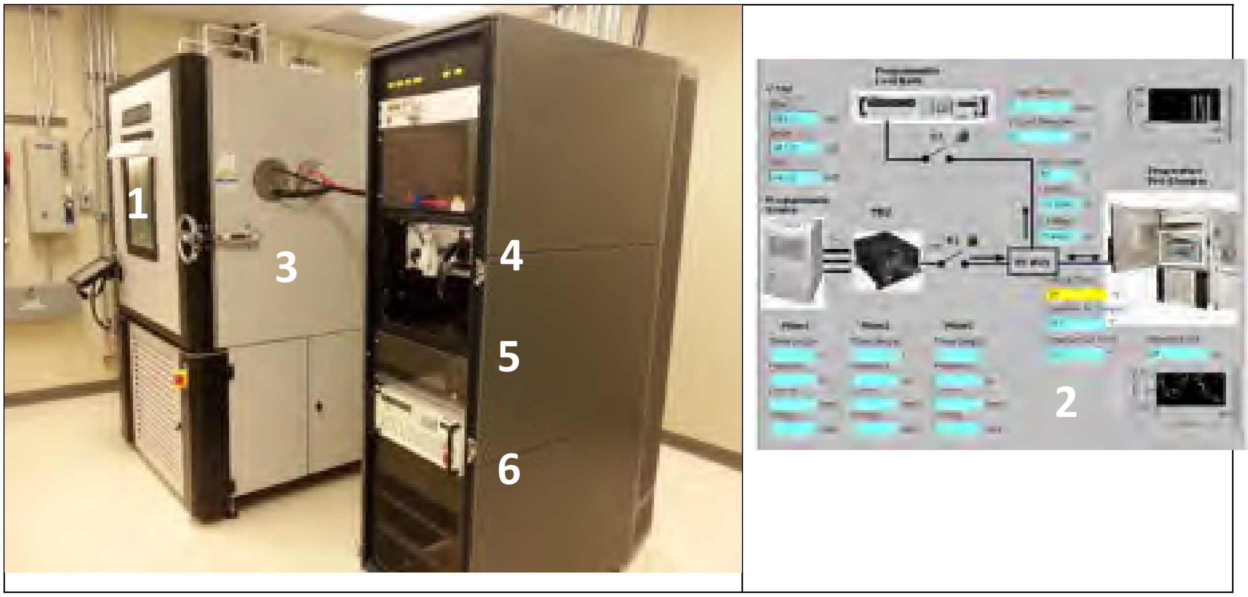

Figure 2-7 Equipment for the tests

CHAPTER 3

NI-CD

3.1 Ni-Cd Introduction

The purpose of this chapter is to present the performance test results of the Ni-Cd battery. All the details about the test procedure are available in chapter 2.

3.2 Flight results at different temperatures

3.2.1 Flight at -40°C

None of the 5 tested flights succeeded. At -40°C, two SOC levels have been tested: 40% and 70%.

- For the flights at 70% SOC:

They all failed because the voltage was too low, on average around 2V at the lowest point. The voltage should be above 12V during the APU starts to be considered realistic in real operation. On the other hand, the current peaks were above the required minimum 500A. See charts 3-1 and 3-3 for more details.

- For the only flight at 40% SOC:

It failed because both the voltage and current were below the minimum threshold. See charts 3-2 and 3-4 for more details.

The chart 3-1 shows the voltage drop during the three APU starts (red curve) for the 70% SOC level. On the third APU start, the voltage reaches 2.7V. The voltage of the three APU starts is below the minimum threshold of 12V.

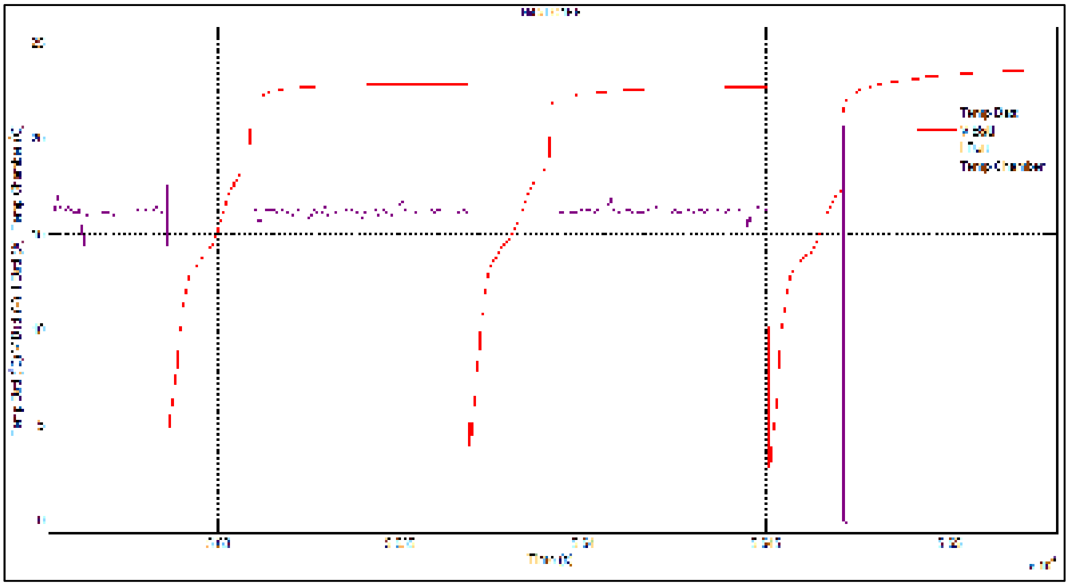

Figure 3-1 Voltage curve during the APU starts (-40°C, 70% SOC)

The chart 3-2 shows the voltage drop during the three APU starts (red curve) for the 40% SOC level. On the third APU start, the voltage reaches 0.2V. The voltage of the three APU starts is below the minimum threshold of 12V.

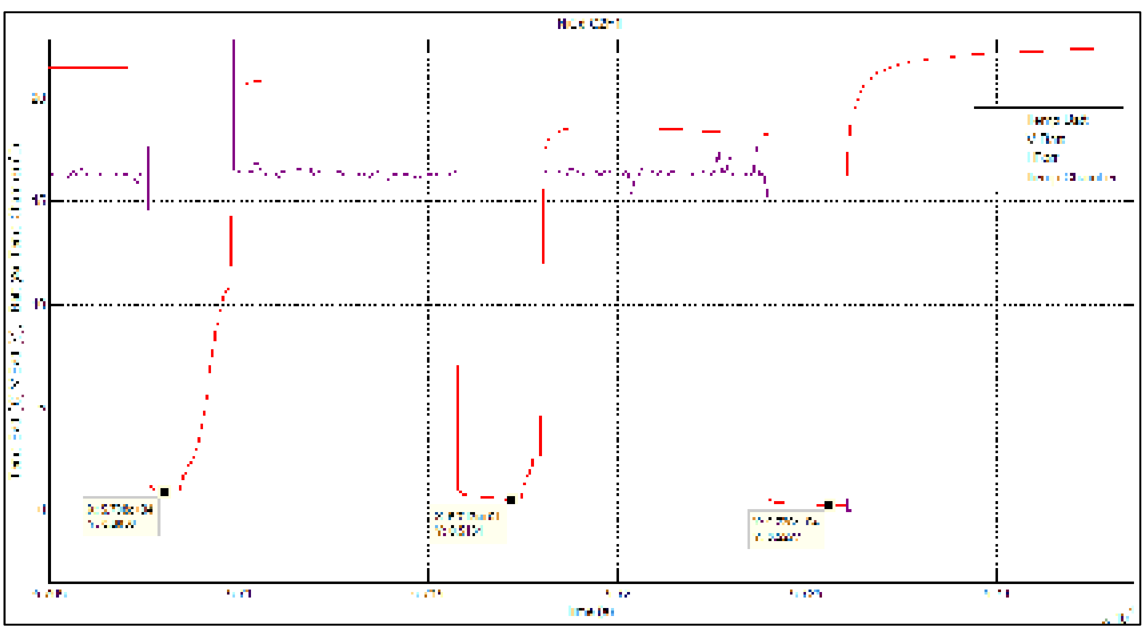

Figure 3-2 Voltage curve during the APU starts (-40°C, 40% SOC)

The chart 3-3 shows the current curve during the three APU starts (purple curve) for the 70% SOC level. All three APU starts are above 750A. The three APU starts are successful from a current point of view only.

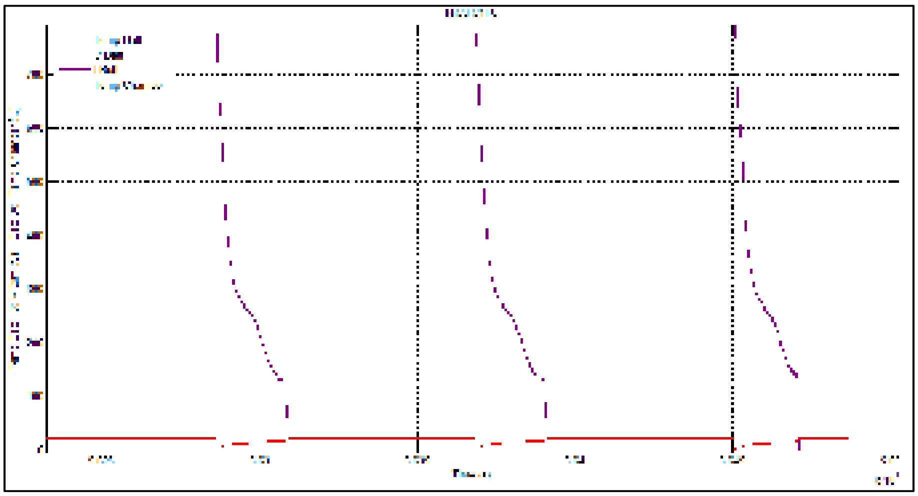

Figure 3-3 Current curve during the APU starts (-40°C, 70% SOC)

The chart 3-4 shows the current curve during the three APU starts (purple curve) for the 40% SOC level. The first current peak only reaches 400A and then decreases for the last two APU starts. The current of the three APU starts is below the minimum threshold of 500A, therefore it is a failure.

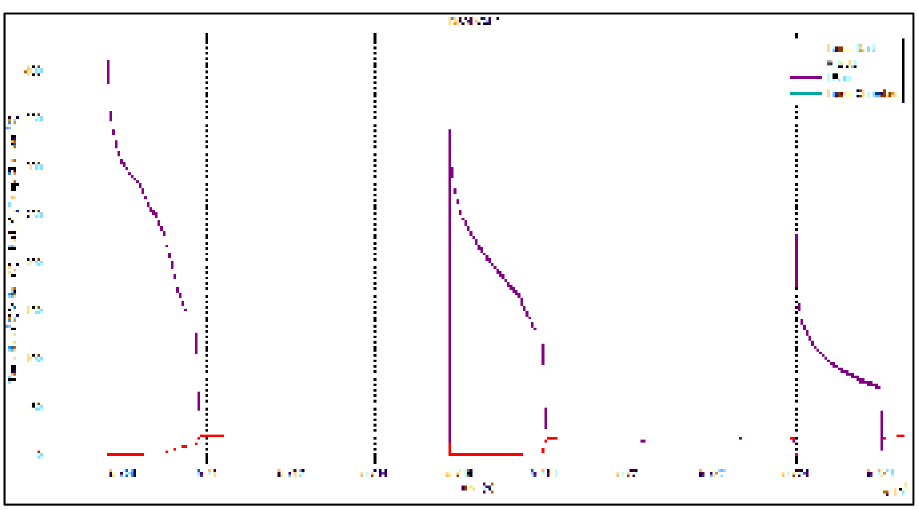

Figure 3-4 Current curve during the APU starts (-40°C, 40% SOC)

3.2.2 Flight at -20°C

At this temperature, 10 flights have been tested at three different SOC levels: 40%, 70% and 90%.

- Flight at 40% SOC and -20°C:

Five flights at 40% SOC have been carried out, all of them have failed. The first flight failed only because of the voltage, which was below the minimum threshold. On the other hand, the current peaks met the requirements of the TDS, minimum 500A. The last flight tested at -20°C and 40% SOC failed because both the current and the voltage during the APU starts were below the minimum threshold. As the tests advanced, the battery had more and more difficulty to do an APU start at -20°C and 40% SOC. See the charts from 3-5 to 3-8 for more details.

The two charts 3-5 and 3-6 show the first flight tested at -20°C and 40% SOC (Cycle 1 flight 1), which successfully passed the APU starts from a current point of view. On the other hand, it failed the APU starts from a voltage point of view. The voltage of the three APU starts is below the minimum threshold of 12V.

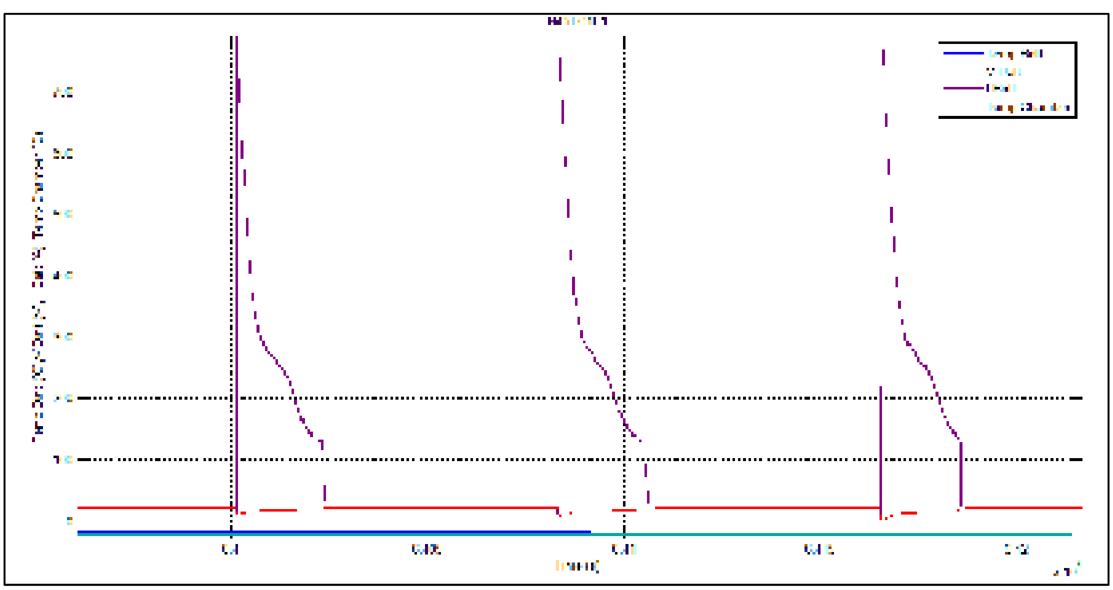

Figure 3-5 Current curve (purple) of the first flight tested at -20°C and 40% SOC

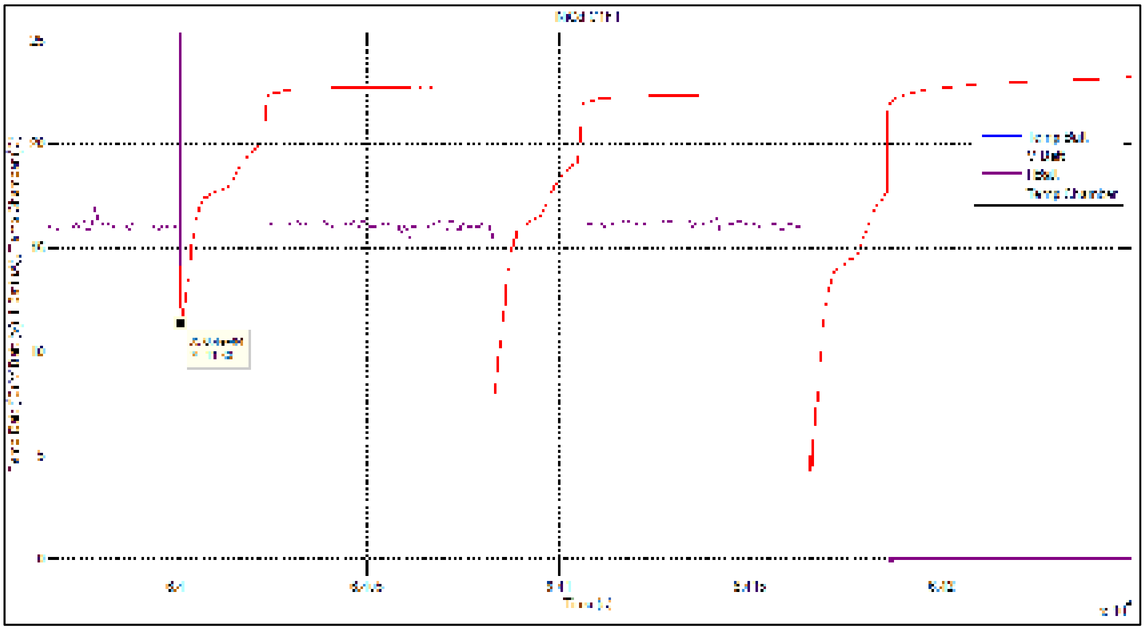

Figure 3-6 Voltage curve (red) of the first flight tested at -20°C and 40% SOC

The two charts 3-7 and 3-8 show the last flight tested at -20°C and 40% SOC (Cycle 3 flight 6), which failed to conduct the APU starts from a current and voltage point of view, both were below the minimum threshold.

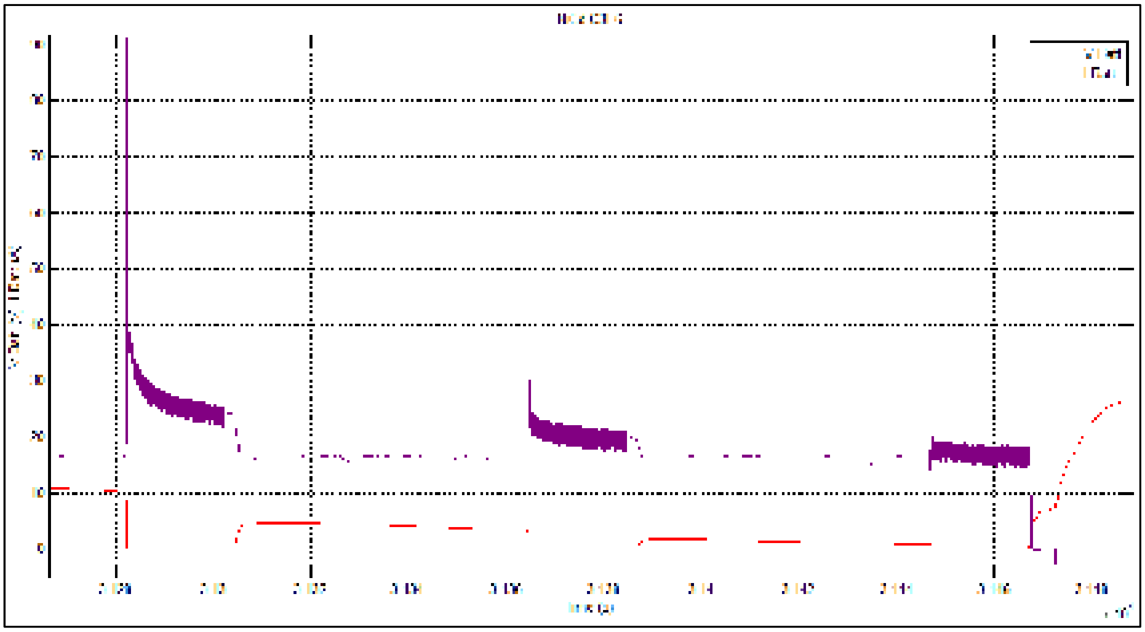

Figure 3-7 Current curve (purple) of the last flight tested at -20°C and 40% SOC

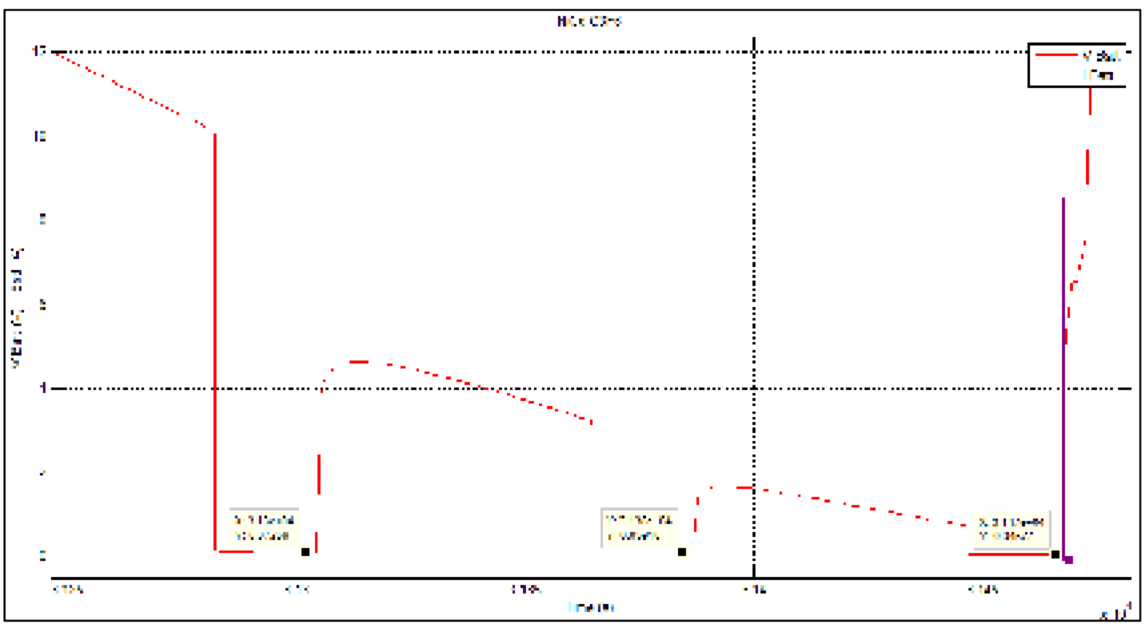

Figure 3-8 Voltage curve (red) of the last flight tested at -20°C and 40% SOC

- Flight at 70% SOC and -20°C:

Four flights at 70% SOC have been carried out, all of them have failed. The tests request to conduct three consecutive APU starts, during the tests at -20°C and 70% SOC the failure happens at the 2nd or 3rd APU start, when the voltage goes under the 12V threshold. See graphs 3-9 and 3-10 for more details. The current peaks are always above 500A.

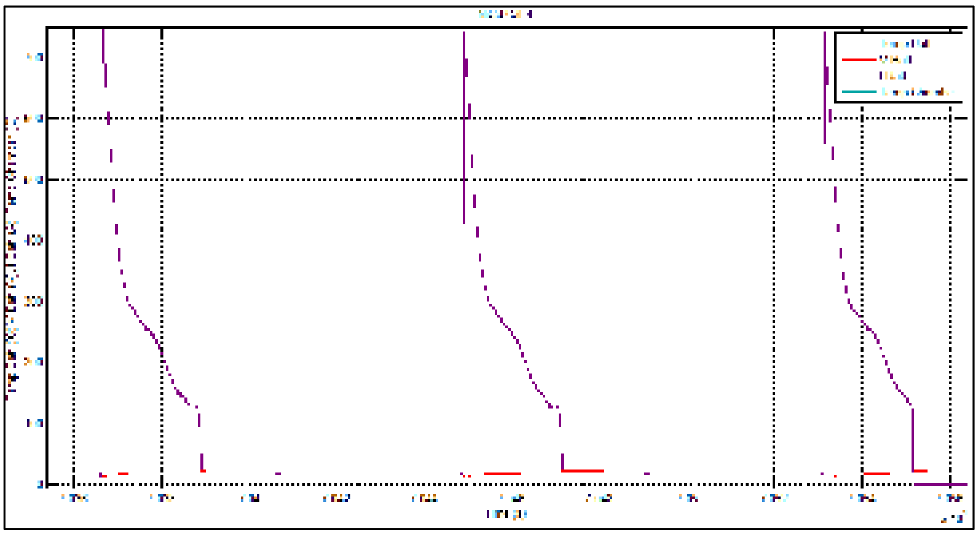

Figure 3-9 Current curve during the APU starts (-20°C, 70% SOC)

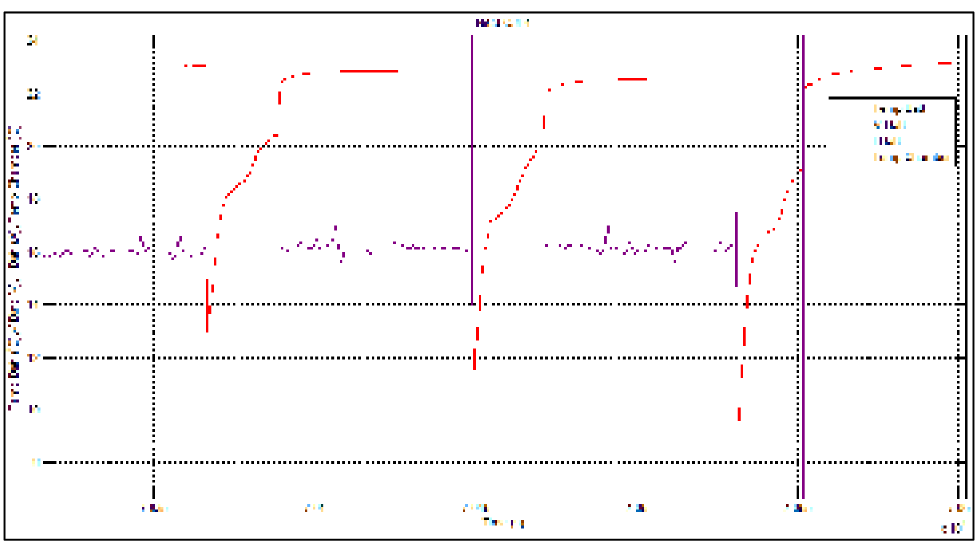

Figure 3-10 Voltage curve during the APU starts (-20°C, 70% SOC)

- Flight at 90% SOC and -20°C:

At -20°C, only the flight at 90% SOC succeeded to pass the three APU starts. As shows the chart 3-11, the voltage level is above the minimum threshold, between 17V and 18V, therefore the voltage is not a parameter causing a failure in this scenario.

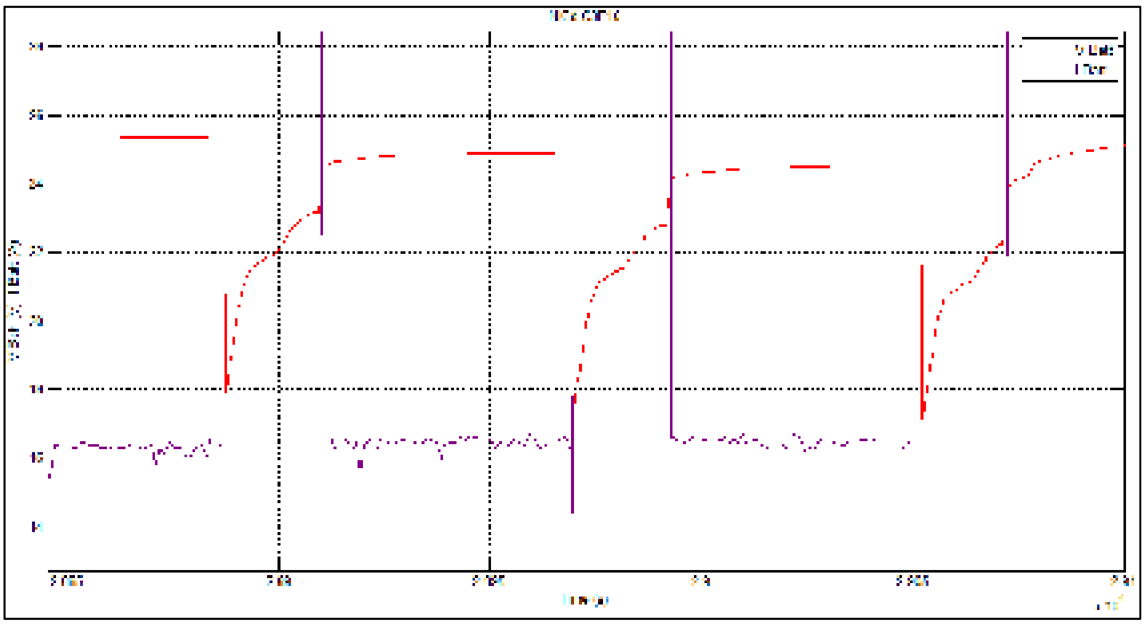

Figure 3-11 Voltage curve during the APU starts (-20°C, 90% SOC)

3.2.3 Flight at 0°C

At this temperature, 3 flights have been tested at three different SOC levels: 70%, 80% and 90%. One of them has failed.

- Flight at 70% and 90% SOC: both flights successfully started the APU.
- Flight at 80% SOC: this test failed. However, this flight almost succeeded because the voltage was at 11.9V and 10.9V during the 2^{nd} and 3^{rd} APU start respectively. The failure happened during the 2^{nd} APU because the voltage was below the minimum threshold of 12V. See graph 3-12 for more details.

The reason why only the flight at 80% SOC failed, is coming from the internal temperature which was at -20°C and not at 0°C as for the two other flights. The flight at 80% SOC stayed on the ground only for 20min and not the usual 10h before the APU starts, therefore the battery did not have the time to sufficiently heat up to reach an internal temperature of 0°C.

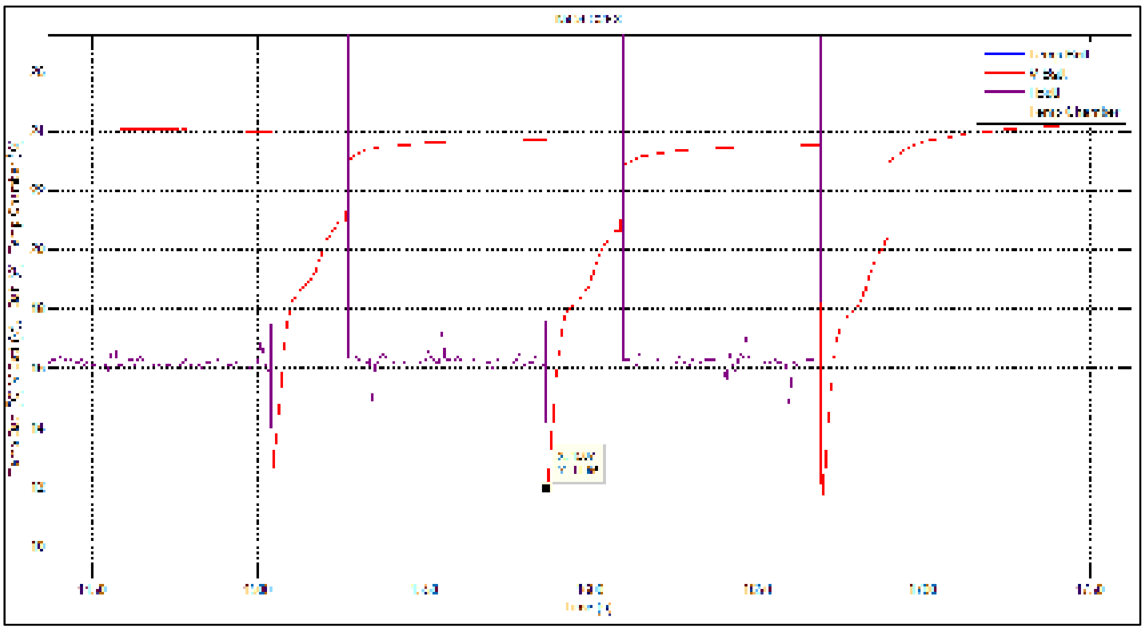

Figure 3-12 Voltage curve during the APU starts (0°C, 80% SOC)

3.2.4 Flight at 20°C

Only one flight has been tested at this temperature with a SOC of 70%. This flight successfully passed the three APU starts.

3.2.5 Flight at 30°C

Two flights have been tested at this temperature with a SOC of 70% and 90%. Both flights successfully passed the three APU starts.

3.2.6 Flight at 50°C

At this temperature all the flights successfully passed the three APU starts. The following SOC have been tested at 50°C: one flight at 40%, three flights at 80% and four flights at 90%.

3.2.7 Flight at 70°C

One of the three flights tested at 70°C failed to successfully pass the three APU starts.

- Flight at 70% and 80% SOC: both flights successfully started the APU.
- Flight at 40% SOC: this flight failed to pass the 3rd APU start, since the voltage was below the minimum threshold of 12V. See graph 3-13 for more details.

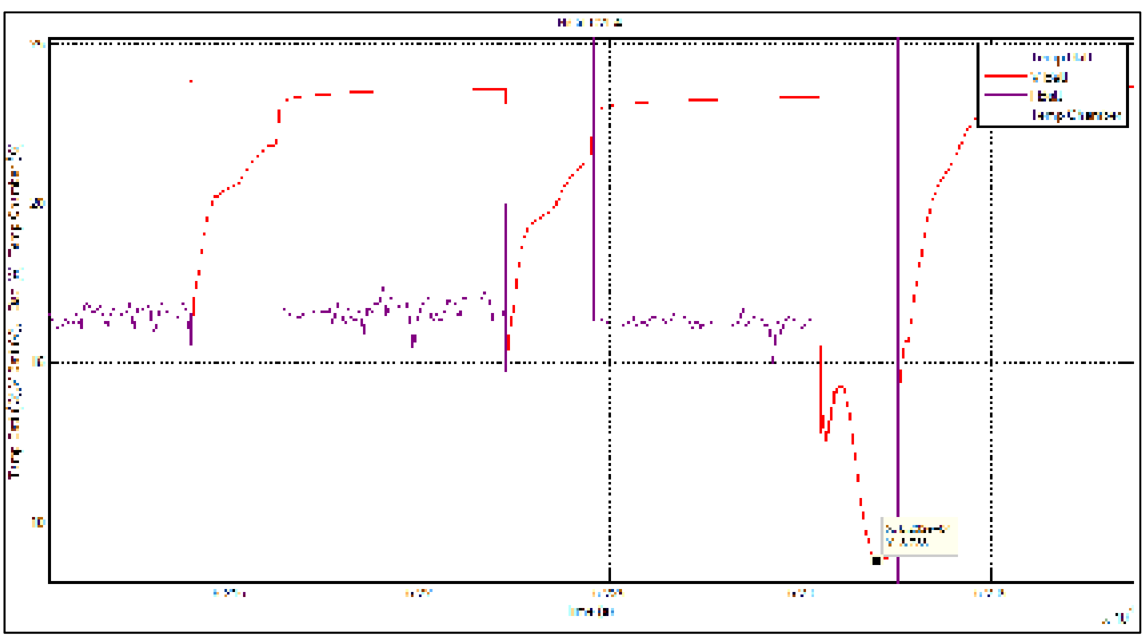

Figure 3-13 Voltage curve during the APU starts (70°C, 40% SOC)

3.2.8 Summary of the flight results at different temperatures

In the table 3-1, the columns failure current and failure voltage mean the current and/or the voltage were below the minimum threshold, therefore leading the test to a failure. See the previous chapter for more details on each result presented in the table 3-1.

Table 3-1 Flight results at different temperatures

Temperature	SOC	Result	Failure current	Failure voltage
-40°C	40%	Failure	Yes	Yes
	70%	Failure	No	Yes
- 20°C	40%	Failure	No / Yes	Yes
	70%	Failure	No	Yes
	90%	Success	No	No
0°C	70%	Success	No	No
	80%	Failure	No	Yes
	90%	Success	No	No
20°C	70%	Success	No	No
30°C	70%	Success	No	No
	90%	Success	No	No
50°C	40%	Success	No	No
	80%	Success	No	No
	90%	Success	No	No
70°C	40%	Failure	No	Yes
	70%	Success	No	No
	80%	Success	No	No

3.3 Observations

3.3.1 Temperature influence on the voltage

The chart 3-14 displays the battery voltage at different temperatures with a 70% SOC. The higher voltage 26.32V is at -20°C and the lower voltage 25.3V is at 70°C. The nominal voltage of the battery is 24V. Between the hottest and the coldest flights, -40°C and 70°C respectively, there is difference of 1V. The voltage at 70°C is 1V lower than the voltage at -40°C.

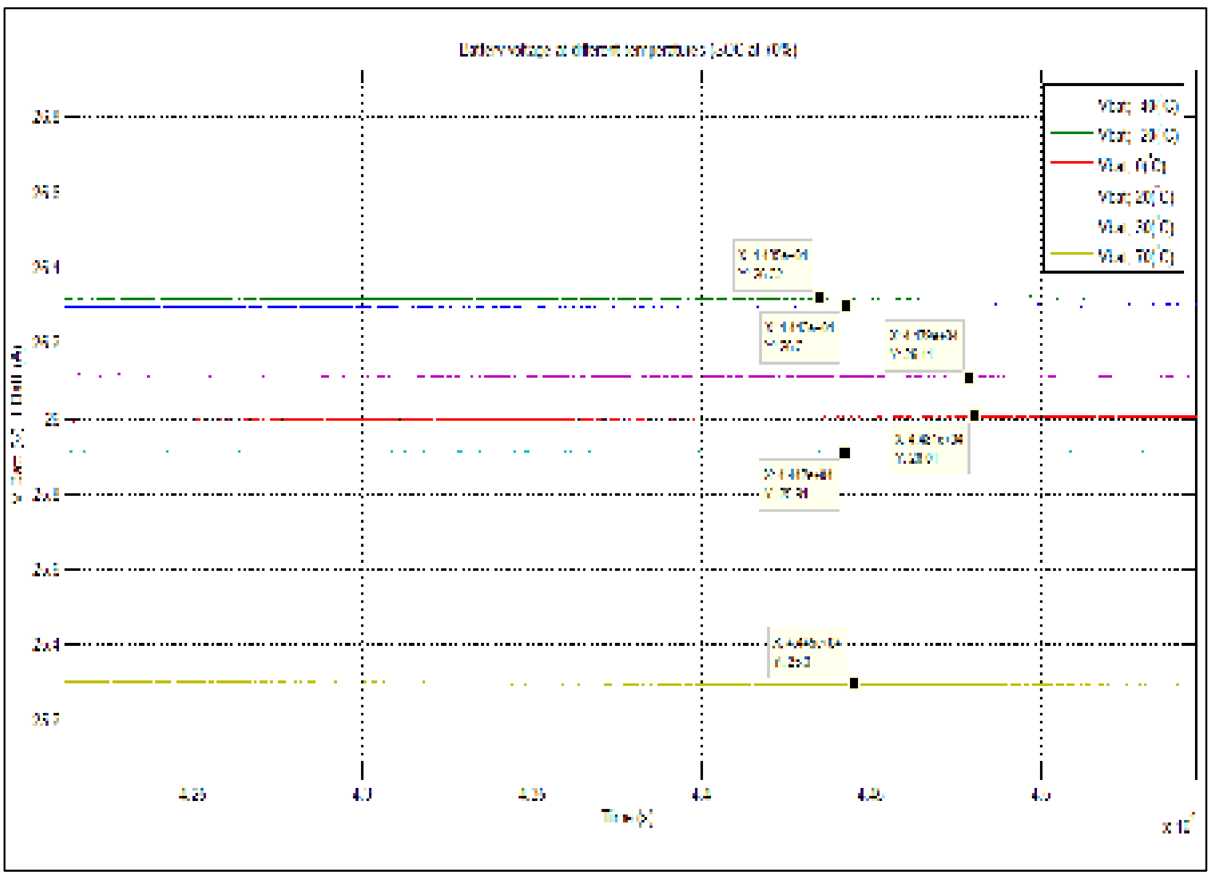

Figure 3-14 Battery voltage at different temperatures (SOC at 70%)

3.3.2 Temperature influence on the voltage during the APU starts

The chart 3-15 displays the battery voltage during the APU starts at different temperatures with a 70% SOC. The lower the temperature, the lower the voltage during the APU starts. Each line going down represents an APU start, there are three APU starts per temperature level. The flights at -40°C and -20°C have failed.

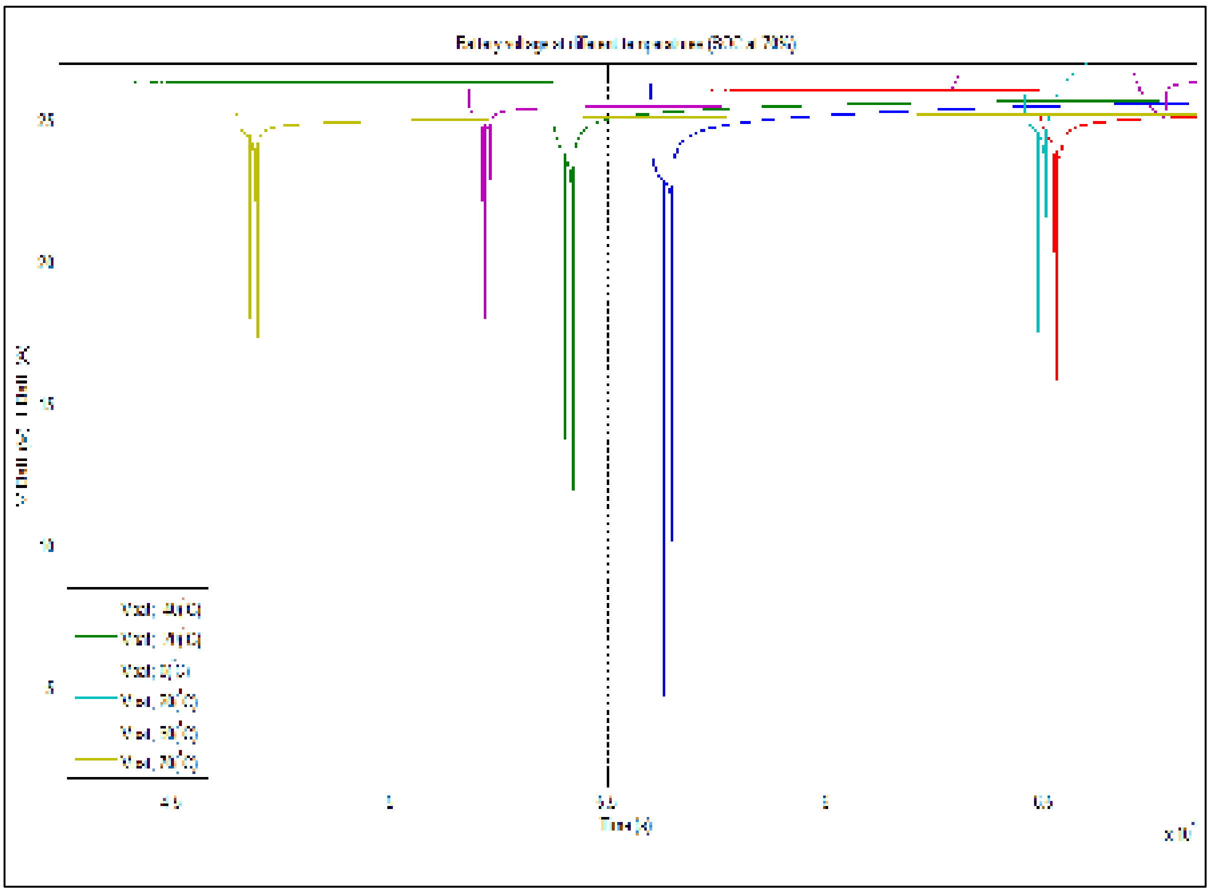

Figure 3-15 Voltage during the APU starts at different temperatures (SOC at 70%)

3.3.3 SOC influence on the voltage

The charts from 3-16 to 3-18 display the battery voltage at different SOC level with a temperature of 50°C. The higher the SOC level, the higher the voltage. At 40% SOC the voltage is at 25.2V and at 90% the voltage is at 26.2V. The nominal voltage of the battery is 24V.

Table 3-2 Battery voltage at different SOC and 50°C

SOC level	Voltage
40%	25.2V
80%	25.9V
90%	26.2V

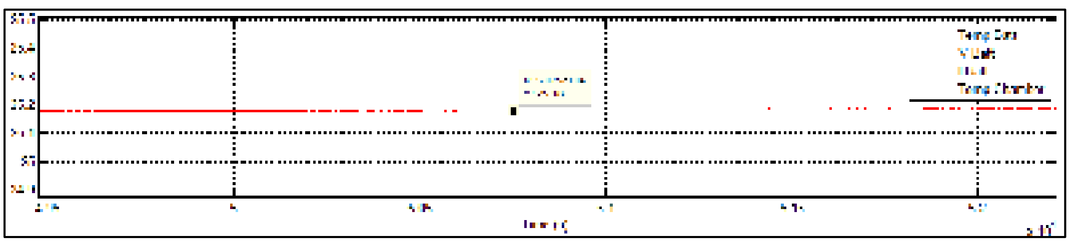

Figure 3-16 Battery voltage at 40% SOC and 50°C

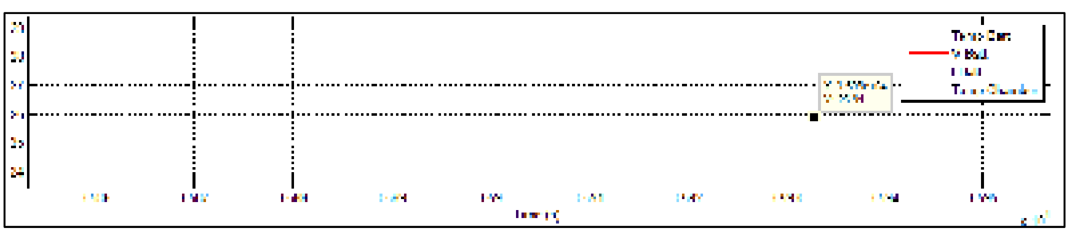

Figure 3-17 Battery voltage at 80% SOC and 50°C

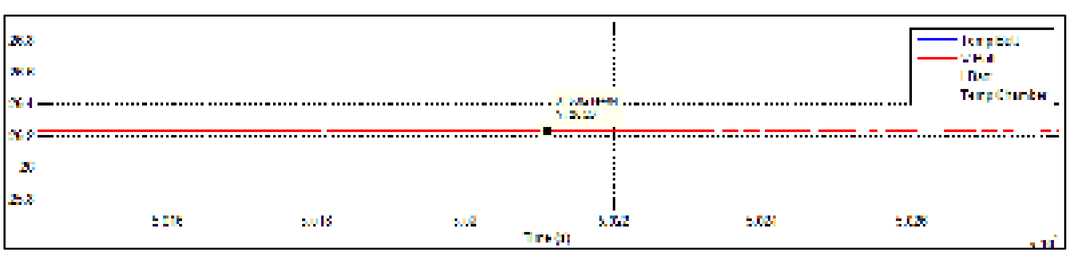

Figure 3-18 Battery voltage at 90% SOC and 50°C

3.4 Statistics about the flights results

3.4.1 Statistic: SOC VS Temperature

The table 3-3 presents the data about the success rate to conduct three consecutive APU starts. The test at 80% SOC and 0°C failed because the aircraft only stayed grounded for 20min. When the aircraft is on the ground only for 20min, the battery does not have the time to heat up and its internal temperature was -20°C. Therefore, the battery capabilities to start the APU are limited by its internal temperature and failures can happen. More details about this flight are available in the chapter *Flight results at different temperatures*, section *Flight at 0°C*. Detailed statistics are available in appendix.

Table 3-3 Success rate of each SOC level according to the surrounding temperature
(If there is an empty cell in the table, this means no tests have been carried out at this temperature and SOC level)

Ni-Cd: Success (%)		**Temperature (°C)**						
		-40	**-20**	**0**	**20**	**30**	**50**	**70**
SOC (%)	**40**	0	0				100	0
	70	0	0	100	100	100		100
	80			0			100	100
	90		100	100		100	100	

The chart 3-19 displays the data of the previous table.

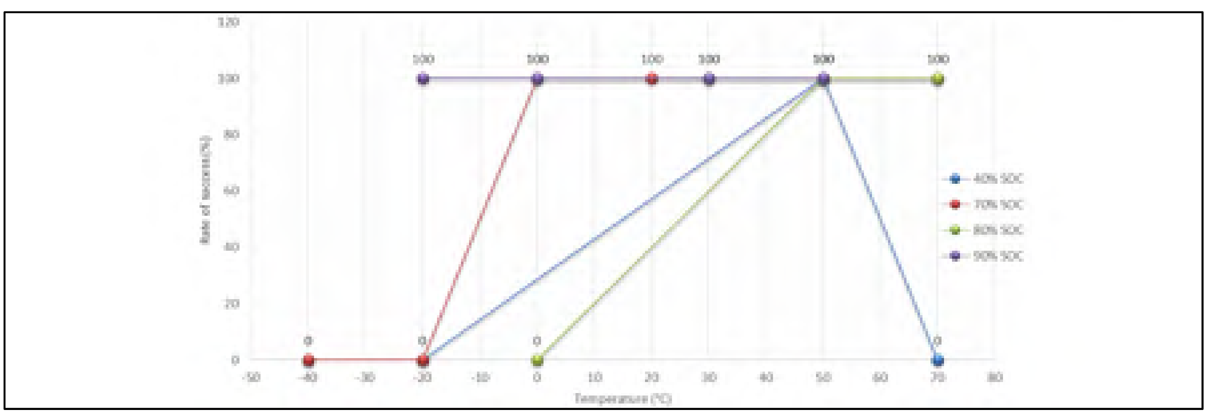

Figure 3-19 Success rate of each SOC level according to the surrounding temperature (some data are not visible on the chart because they are superimposed)

3.4.2 Statistic: Success rate VS Temperature

The graph 3-20 displays the success rate of each temperature used for the tests, without taking into account the SOC. It is another way to display the data from the section 3.4.1.

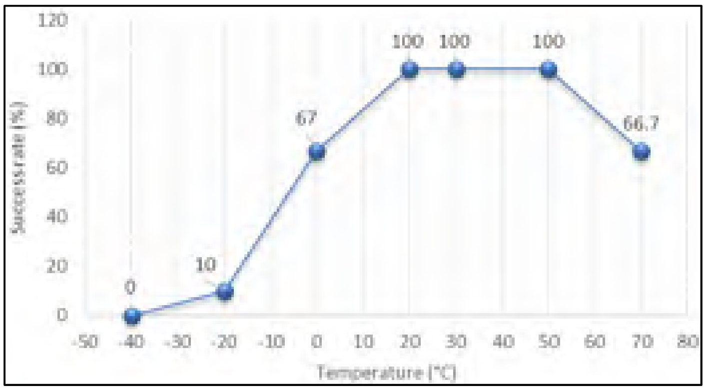

Figure 3-20 Success rate VS Temperature

3.4.3 Statistic: Success rate VS SOC

The graph 3-21 displays the success rate of each SOC level used for the tests, without taking into account the different temperatures. It is another way to display the data from the section 3.4.1.

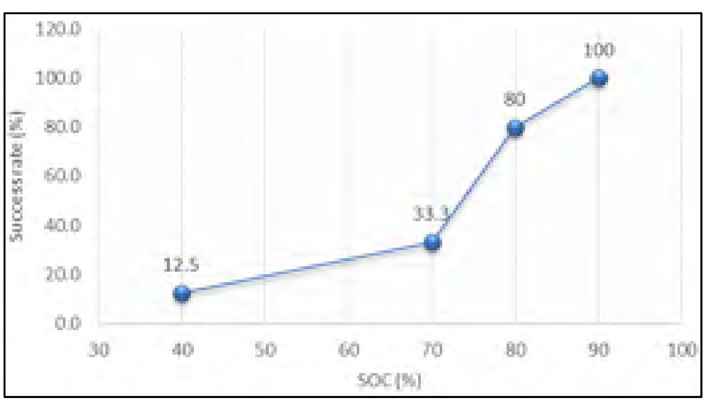

Figure 3-21 Success rate VS SOC

3.5 Ground phase of 20 minutes

During the ground phase, the aircraft can stay on the ground for 20 minutes or 10 hours at a designated temperature. Therefore, when the aircraft is staying on the ground for only 20min at a new surrounding temperature, the internal temperature of the battery does not have the time to significantly change. For example, during the cycle 3 flight 10, the internal temperature of the battery was at 22.6°C at the beginning of the 20min period on the ground and at 16.3°C at the end, while the surrounding temperature was at -20°C. Thus, it can be observed that during this short period of time, the battery has only decreased its internal temperature by 6.3°C. See the chart 3-22 for more details.

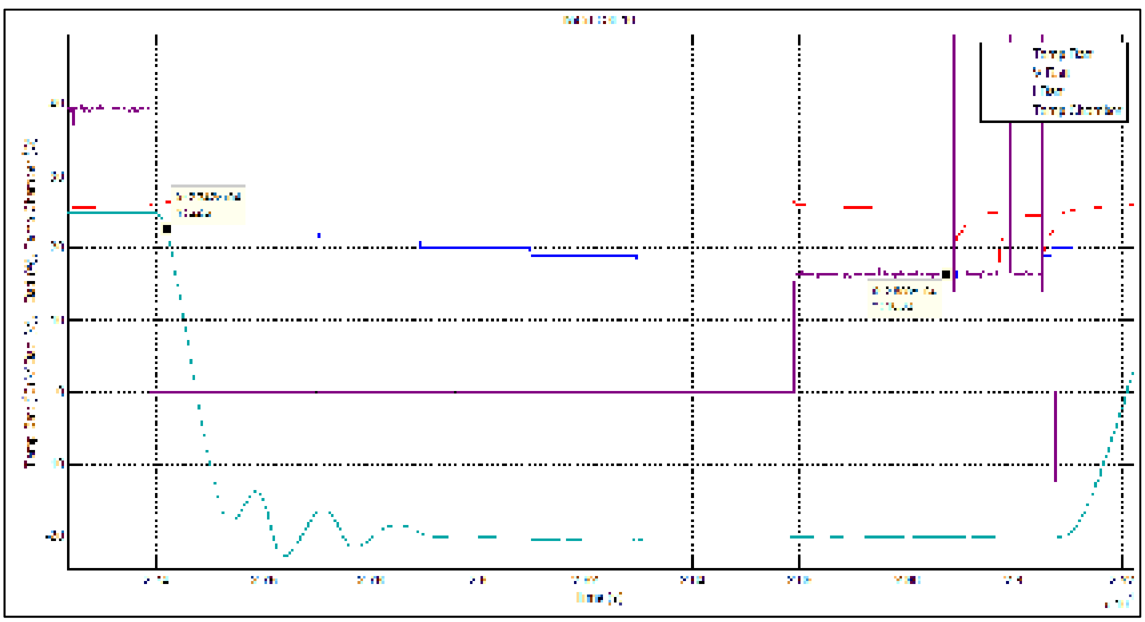

Figure 3-22 Internal temperature during a transit flight of 20 minutes at -20°C (cycle 3, flight 10)

The main point to remember in this chapter is, in real conditions, after a flight at -56°C the internal temperature of the battery will only increase by a few degrees while staying on the ground for only 20min. Therefore, the battery can have difficulties to conduct three APU starts, since it is known that the battery performances are reduced at low temperatures.

The table 3-4 presents the internal temperatures of the battery at the end of the flight sequence at -56°C.

Table 3-4 Internal temperatures of the battery at the end of the flight sequence at -56°C

Flight sequence	Flight time	Internal temperature at the end
Short	96 min	Between 0°C and 10°C
Medium	210 min	-20°C
Long	618 min	-45°C

3.5.1 Result of the tests with a ground phase of 20 minutes

At 90% SOC, all the flights successfully passed the three consecutive APU starts.

At 80% SOC, the flight almost succeeded to pass the three APU starts, it failed because the voltage was slightly below the 12V threshold. During the 2nd APU start the voltage was at 11.9V and during the 3rd APU at 10.9V. The internal temperature of the battery was -20°C. See graph 3-23 for more details.

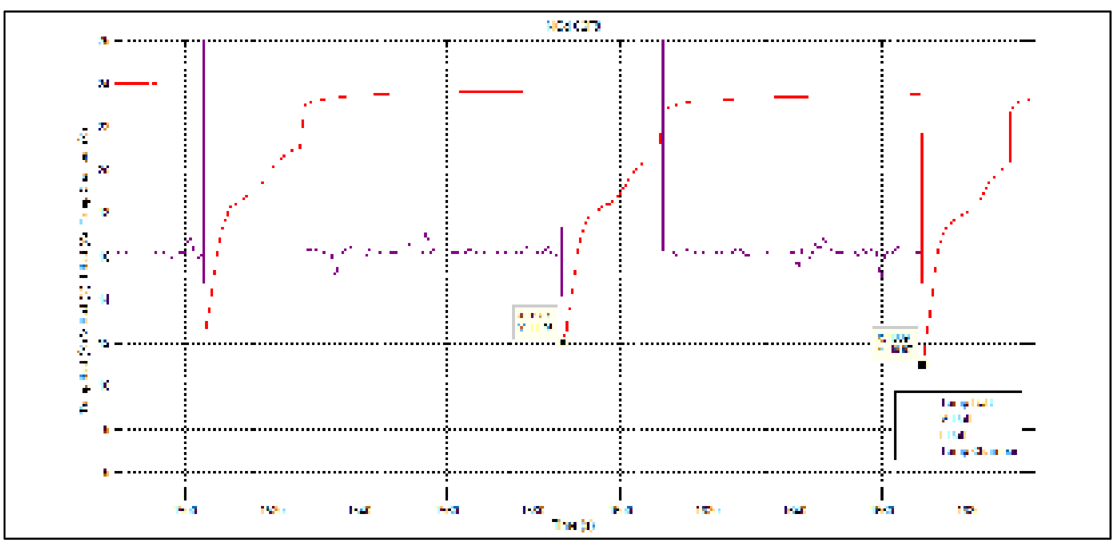

Figure 3-23 Voltage curve during the APU starts after a transit flight of 20 minutes (80% SOC, internal temp -20°C)

At 40% SOC, all the flights failed. For this case, one of the potential reasons for failure is coming from the SOC, not the temperature, because the battery does not have enough energy to fulfil the demand. The internal temperature of the battery was at 25°C while the surrounding was at a -20°C. More details about these flights are available in the chapter *Flight results at different temperatures*, section *Flight at -20°C*.

3.6 Flights with 80%+ SOC

For the flights with "real" SOC of 80% and 90%, 12 flights have been tested and only 1 flight has failed to pass the three APU starts (flight at 80% SOC and 0°C). Furthermore, only one flight has been tested at -20°C, all the other tested flights were at 0°C and above, up to 70°C. These flights are characterised as real because the TDS says "No take-off unless SOC is 80% (rule in STD DO311)".

3.7 Capacity check after 32 flights

The battery has lost 17.3% of its capacity after 32 flights. With a discharge current of 43A, the battery now last 2977s instead of 3600s. Which gives the battery a capacity of 35.57Ah instead of 43Ah. The table 3-5 compares the data of the brand new battery and the same battery after 32 fights with no maintenance.

Table 3-5 Battery capacity - New VS after 32 flights

	Brand new battery	**Battery after 32 flights**
Capacity (Ah)	43	35.57
Capacity (%)	100	82.72
Capacity check (s)	3600s = 1h	2977s = 50min

The graph 3-24 presents the capacity checks of the new battery, directly after unpacking it and the same battery after 32 flights. The battery is considered empty once it goes under 20V.

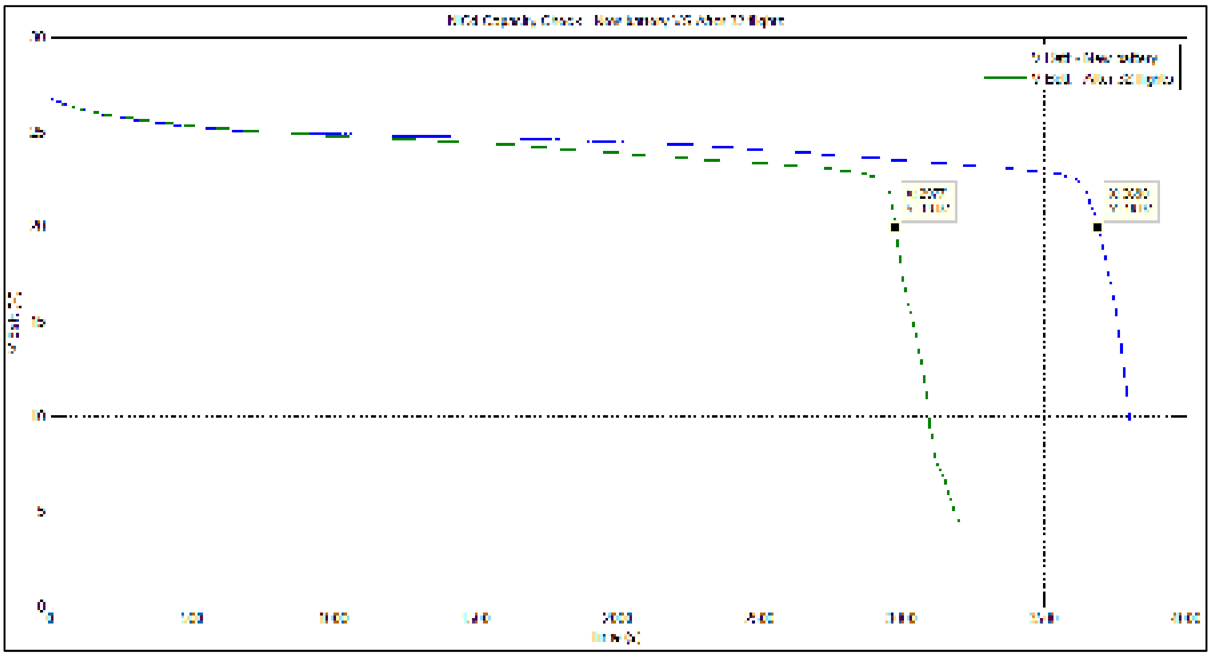

Figure 3-24 Capacity check- New battery VS After 32 flights

3.7.1 Procedure used for the capacity check

The capacity check has been done according to the procedure available in the component maintenance manual from the battery manufacturer. First, the complete discharge, the residual capacity is discharged down to 20V, then the battery is placed with shorting resistors overnight. After this step, the charge starts, which means charging first at 21.5A until the battery reaches 31V and then for the second step, the battery had been charged for 3h30 at 4.3A. At the end of the second step the battery was at 33.5V, equivalent to 1.675V per cell.

3.8 Conclusion

During the flight simulations, the Ni-Cd battery has executed 32 flights, 16 were successful and 16 failed. Among the failed tests, three of them failed with less than 1V below the minimum threshold. The main source of failure for all the flights was the voltage.

The cold temperatures reduce the battery performances at almost any level of SOC. The battery can handle the hot temperatures more easily, from 0°C to 70°C.

The battery has lost 17.3% of its capacity after 32 flights. Now, if the fact that the battery has lost capacity over time is put aside and if just the tests with a SOC of 80% and more are considered; it can be seen that only one flight has failed to conduct three consecutive APU starts. This flight which failed, almost succeeded to pass the three APU starts. This means, even with this capacity loss, the battery has still enough energy to conduct three consecutive APU starts, since for the take-off it is mandatory to have a minimum of 80% SOC.

One of the potential reasons to explain the loss in capacity is that the battery is aging faster with the high currents used to start the APU and the extreme temperatures.

According to the test results, a recommendation for the Ni-Cd would be to add a heating device around the battery, thus the battery will never be too cold to start an APU. Since, after a flight at -56°C followed by a transition period of only 20min on the ground, the battery does not have the time to sufficiently heat up to start an APU.

CHAPTER 4

LI-ION

4.1 Li-Ion Introduction

The purpose of this chapter is to present the performance test results of the Li-Ion battery. The Li-Ion batteries have been tested in the following order: First the S1, then the S2 and to finish the S2N battery. This chapter on the Li-Ion battery has been started by Romain Bonnin, with the Li-Ion S1 & S2, during his master thesis and then I, David Herzog, took over the Li-Ion project with the S2N. I have continued and updated the content of the complete Li-Ion study, with the test results of the three Li-Ion batteries.

4.2 Observations

The observations made in this chapter can be applied to the S1, S2 and S2N batteries.

4.2.1 Temperature influence on the voltage

The tests have showed the great influence of the temperature on the battery voltage. According to the internal temperature of the battery, the voltage changes. In the figure 4-1, 5 different voltages are displayed. For each curve the SOC of the battery is fixed at 70%. The battery has spent 10 hours (cold soak) at a designated temperatures before the measurement. The figure 4-1 compares 5 different temperatures.

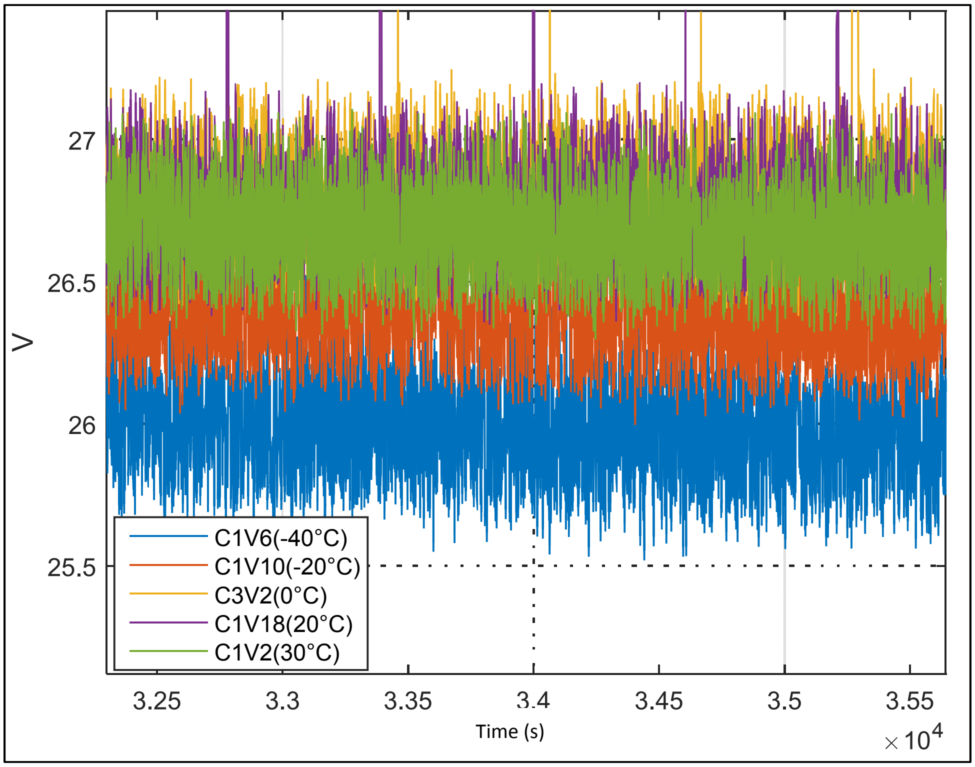

Figure 4-1 Battery voltage at different temperatures (SOC at 70%)

According to the graph 4-1grap, the voltage dropped of 0.8V between 0°C and -40°C. A voltage drop of 0.8V means a drop of 114mV per cell (VL30P cell operates between 4000mV and 3300mV). This greatly reduces the capacity of the cell and represents more than 16% of its charge state (1mV = 0.143 % SOC of a cell).

4.2.2 Temperature influence on the voltage during an APU

The temperature influences significantly the performance of the battery. If the battery is used at high temperatures, it will accelerate the reaction of cells and can cause an exothermic reaction. On the other hand, if the cells work at excessively low temperatures, the electrolyte may begin to crystallize and depolarization could happen. The figure 4-2 shows the voltage during an APU start. The battery spend 10h on the ground at a specific temperature before the APU starts are performed. All tests were made with a battery charged at 40% SOC. Only 2 APU starts are displayed, since the chart 4-2 is only here to show the influence of the temperature on the voltage for each test at different temperatures. For all the tests, the current peak corresponding to the lowest voltage value is 745A. The blue line below 20V is corresponding to the flight at 70°C.

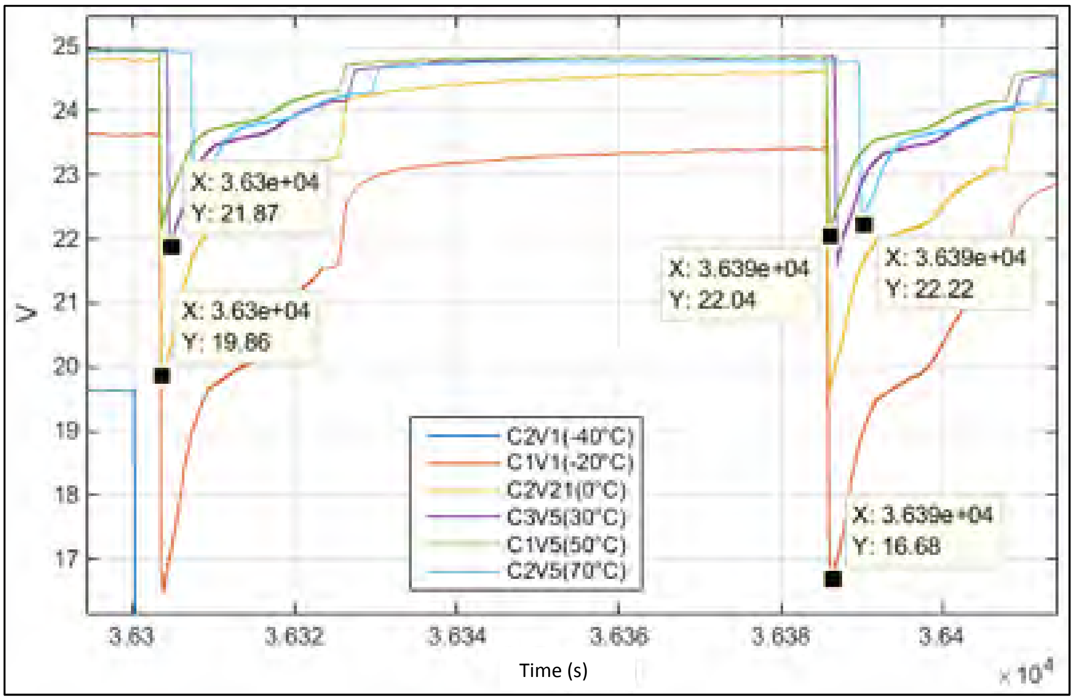

Figure 4-2 Voltage during an APU start at different temperatures (SOC at 40%)

These voltage curves illustrate the influence of the temperature on the performance of the battery. Before the APU starts, there is a difference of 5.7V between the flight at 70°C and the flight at -40°C. During this period, the battery was discharged at 20A for 5 min. During the APU starts, the battery behavior is relatively similar to when the battery was at 20°C and above. Between 30°C and 70°C there is a small difference of 0.35V. It can be seen that it is more difficult to perform an APU start at negative temperatures. When the battery is tested at -20°C, the voltage drops by 7V when the discharge current peak reaches its max value of 745A. On the other hand, for a flight at 30°C, the voltage drop is 3.13V. Moreover, the test at -40°C failed. At negative temperatures, the cells impedance significantly increase, which result in high voltage drop across the battery cells.

4.2.3 Voltage drop during an APU start at different SOC

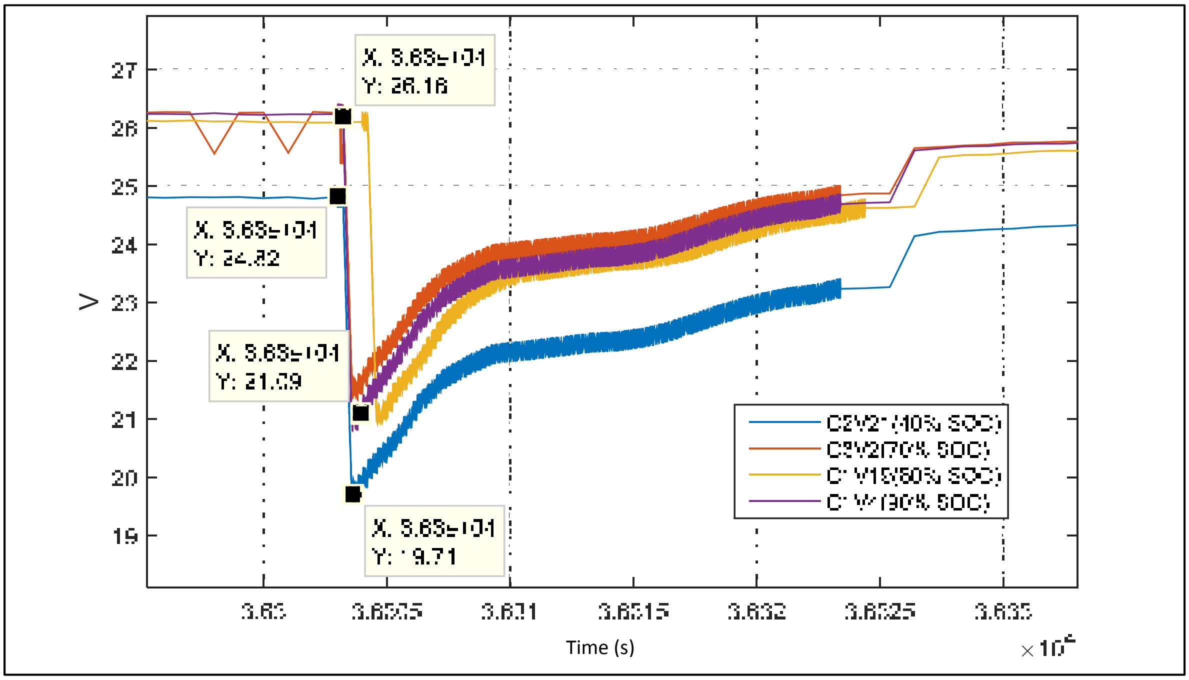

Figure 4-3 Voltage drop during an APU start at different SOC (ambient temperature at 0°C)

The open circuit voltage changes according to the battery state of charge. However, it is interesting to see the voltage difference when the same current peak is applied at different SOC. The figure 4-3 shows the battery voltage drop during an APU start with an ambient temperature at 0°C and with four different SOC: 40 %, 70 %, 80% and 90%. During the APU start, with an initial SOC of 90 %, the battery voltage dropped by 5.07V while at 40% SOC it dropped by 5.11V. Therefore, the voltage drop difference is negligible between the different SOC during an APU start. Furthermore, the internal temperatures of each SOC test differ from 1 or 2°C, which can explain the small difference in the voltage drop. However, the influence of the SOC on the voltage can be seen before the APU start. There is a 1.34V voltage difference between the battery charged at 90% and the one at 40 %.

4.2.4 SOC drop during APU starts at different temperatures

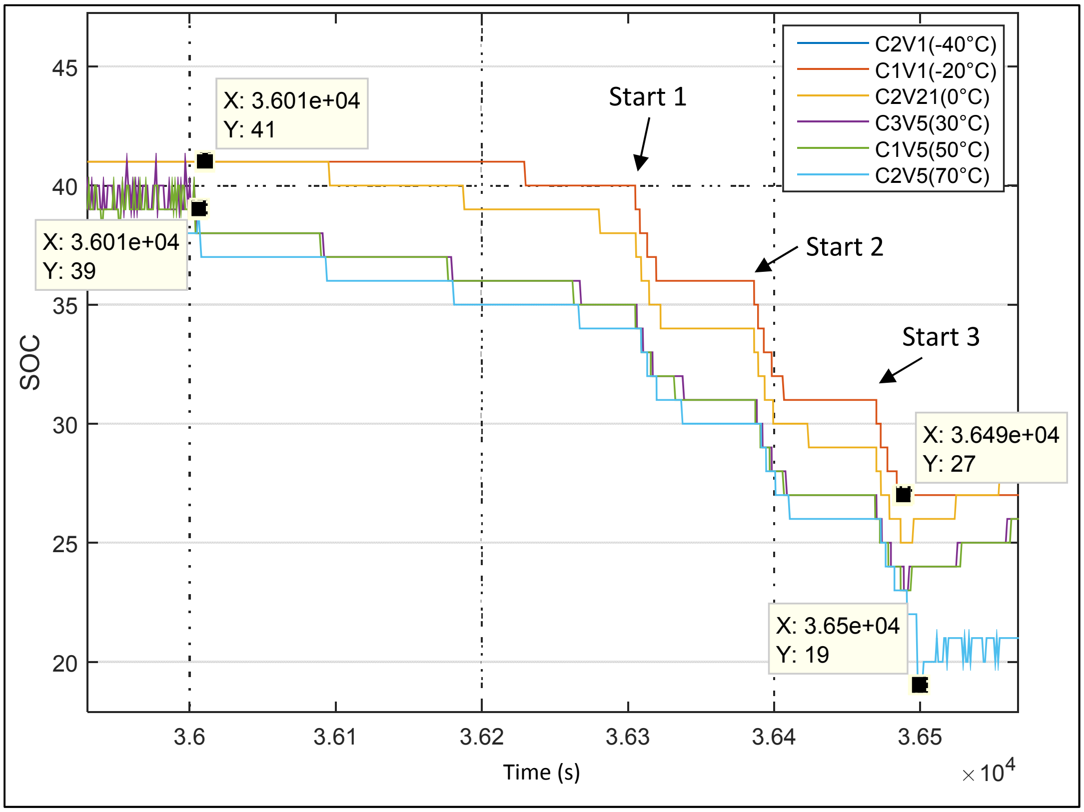

Figure 4-4 SOC drop during the APU starts at different temperatures
(initial SOC at 40%)

According to the figure 4-4, the SOC drop is more substantial when the battery is at high temperatures. After the three APU starts, the flight at -20°C lost 14% of SOC whereas at 70°C, the battery has lost 20 %. For all temperatures, the APU starts were completed entirely. It was found previously, that the voltage is increasing at high temperature, above the reference voltage. Therefore in this test, the voltage is artificially increased by the temperature at 70°C, which makes the voltage drop more important at high discharge rate. This can explain why the SOC drop is more important at 70°C compared to -20°C.

4.2.5 Charging time after the APU starts at different temperatures

As mentioned earlier, before the takeoff, the pilot has three attempt to start the APU otherwise the aircraft will be barred from take-off. Once started, the batteries must be recharged to 80 % SOC. This period must be as short as possible. According to the standards, a battery must be able to be recharged to 80% in less than 1 hour with an initial SOC of 20%.

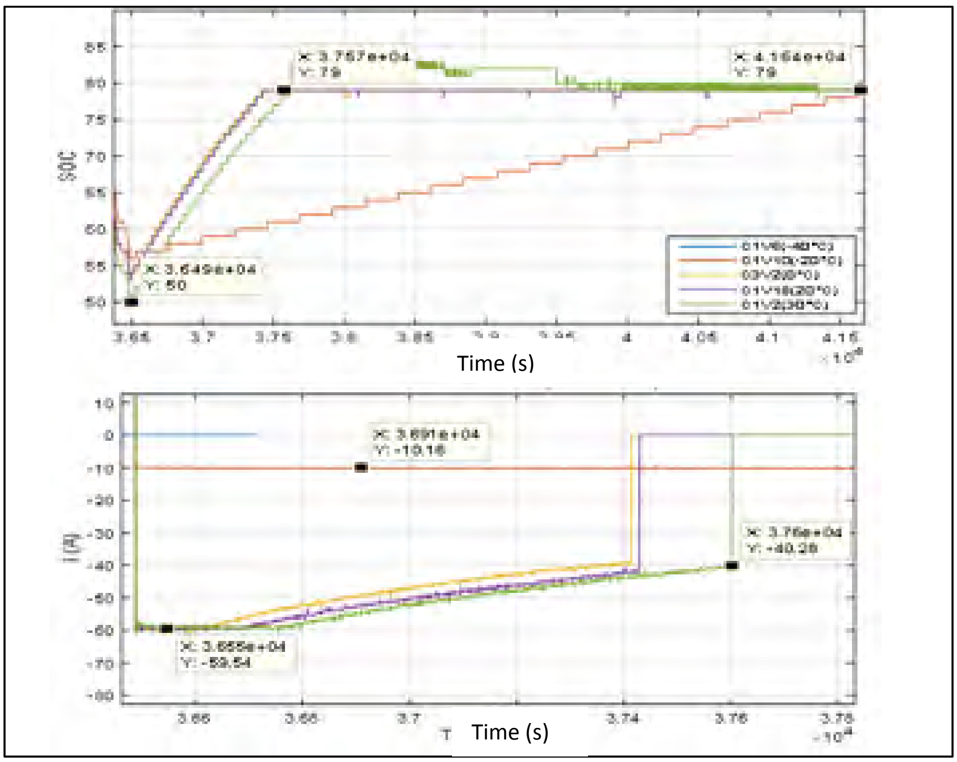

Figure 4-5 Charging time after the APU starts at different temperatures (initial SOC: 70%)

The figure 4-5 shows that the battery charging time lasted longer during the test at -20°C. At -20°C, charging the battery takes 85 minutes for the SOC to increase by 23%, while for a flight higher than 0°C it takes only 18 minutes to increase the SOC by 30%. The difference in charging time, is due to the charging current. During a flight at -20°C the battery is charged with a current of 10A, while for higher temperatures, the charging current starts at 60A and gradually decreases when reaching the end of the charge. During our tests, we charged at constant voltage and the battery BMS controlled the charging current.

4.2.6 Thermal transfer

The graph 4-6 shows the thermal transfer of the battery at different temperatures. Staple curves represent the temperature of environmental chamber and the continuous curves represent the internal temperature of the battery. For each temperature level, it takes more than 8 hours for the internal temperature of the battery to be close to the chamber temperature at + or -4°C. The battery has a high thermal inertia.

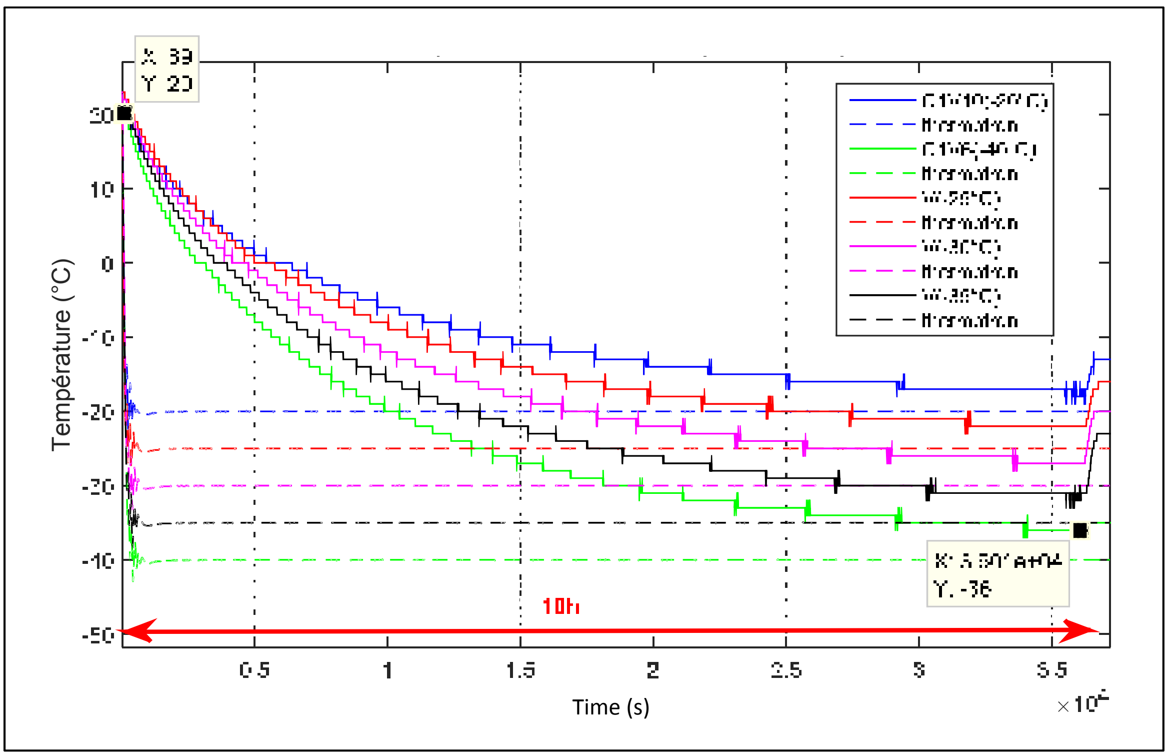

Figure 4-6 Thermal transfer at different temperatures (SOC at 70%)

4.3 Statistics about flights results

4.3.1 S1 Battery

The table 4-1 presents the data about the success rate to perform three APU starts for the battery S1. For the 20°C and 30°C temperatures, the success rate was not 100% everywhere since the aircraft was only staying grounded for 20min. When the aircraft is on the ground only for 20min, the battery does not have the time to heat up and its internal temperature stays between -14°C and -26°C. Therefore, the battery capabilities to perform three APU starts are limited by its internal temperature and failures can happen.

Table 4-1 Battery S1 - Success rate of each SOC level according to the surrounding temperature (If there is an empty cell in the table, this means no tests have been carried out at this temperature and SOC level.)

S1 - Success (%)		**Surrounding temperature (°C)**						
		-40	**-20**	**0**	**20**	**30**	**50**	**70**
SOC (%)	**40**		28	100	80	70.8	100	
	70		100	100	100	100		
	80			100	80	80	100	
	90		100	100	100	100		

The chart 4-7 displays the data of the previous table.

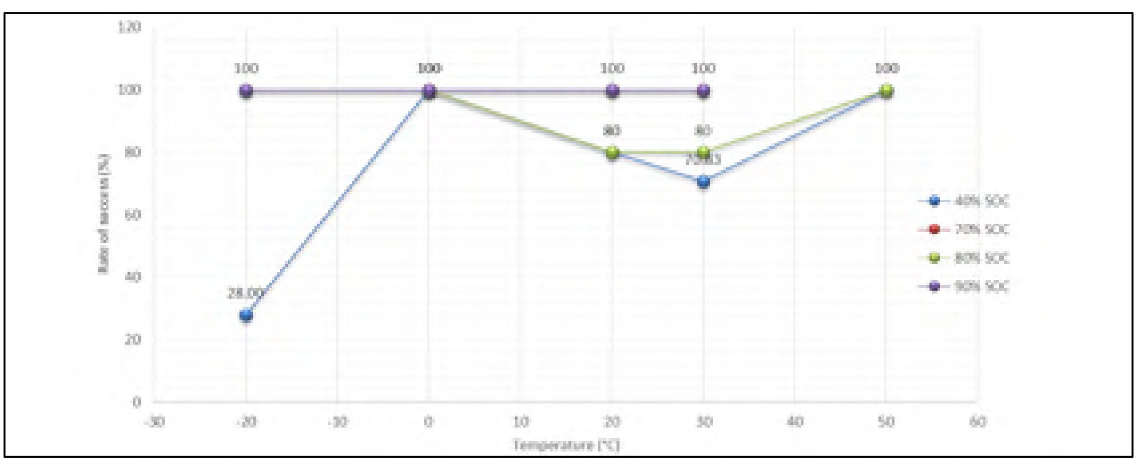

Figure 4-7 Battery S1 - Success rate of each SOC level according to the surrounding temperature (some data are not visible on the chart because they are superimposed)

4.3.2 S2 Battery

The table 4-2 presents the data about the success rate to perform three APU starts for the battery S2. The test spectrum has been broadened on the S2 battery. Therefore, more tests have been carried out at -35°C, -30°C and -25°C. However, several tests have been carried out only once, thus, some results in the table 4-2 must be taken with precaution. More details are available in appendix.

Table 4-2 Battery S2 - Success rate of each SOC level according to the surrounding temperature (If there is an empty cell in the table, this means no tests have been carried out at this temperature and SOC level.)

S2 - Success (%)		**Surrounding temperature (°C)**									
		-40	**-35**	**-30**	**-25**	**-20**	**0**	**20**	**30**	**50**	**70**
SOC (%)	**40**	0				57.14				100	0
	70	0	100	100	100	80		100	100		
	80						100			100	0
	90					100	100		100	100	

The chart 4-8 displays the data of the previous table.

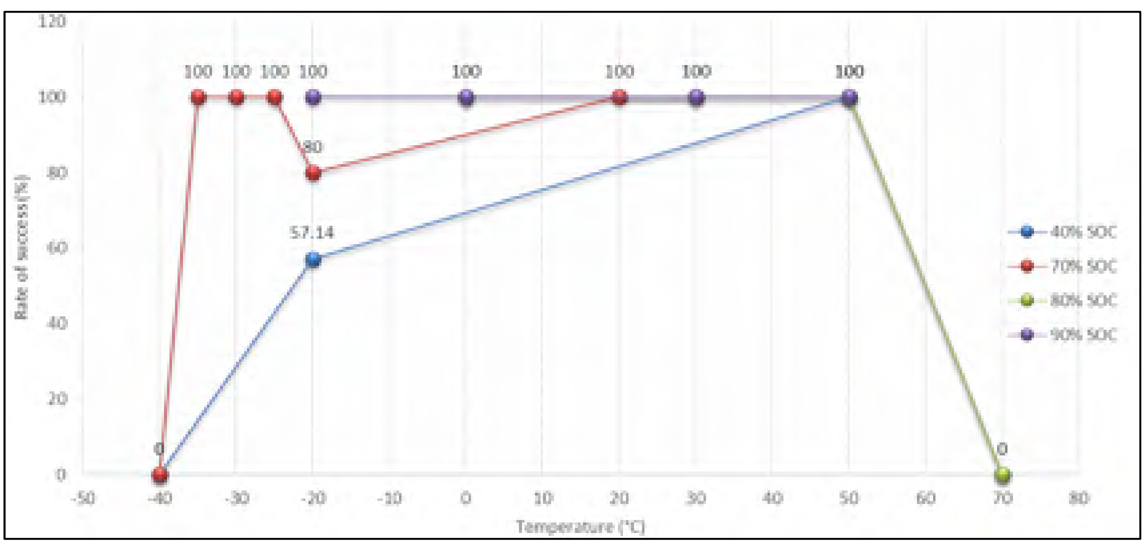

Figure 4-8 Battery S2 - Success rate of each SOC level according to the surrounding temperature (some data are not visible on the chart because they are superimposed)

4.3.3 S2N Battery

The table 4-3 presents the data about the success rate to perform three APU starts for the battery S2N. The tests for the S2N battery have been made specifically to assess the cold temperatures. For the S2N battery, the APU start curve has been changed and the max APU current is lower compared to the APU curve used for the S1 and S2 batteries.

Table 4-3 Battery S2N - Success rate of each SOC level according to the surrounding temperature (If there is an empty cell in the table, this means no tests have been carried out at this temperature and SOC level.)

S2N Success (%)		**Surrounding temperature (°C)**						
		-40	**-20**	**0**	**20**	**30**	**50**	**70**
SOC (%)	**40**							
	70	0	57.14		100			
	80			100				
	90		100	100				

The chart 4-9 displays the data of the previous table.

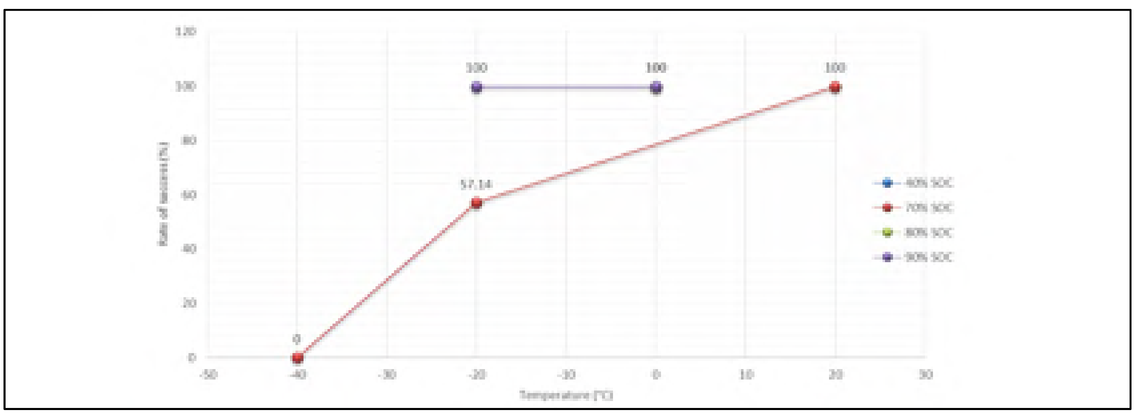

Figure 4-9 Battery S2N - Success rate of each SOC level according to the surrounding temperature (some data are not visible on the chart because they are superimposed)

ATTENTION about the statistics results: Each SOC level has not been tested under the same conditions, thus, not the same amount of flights at the same temperatures. See annex for more details.

4.4 Issues

4.4.1 Transit flight of 20 minutes

On landing, a new room temperature is set and the aircraft can stay on the ground for 10 hours or 20 minutes (transit flight) according to the flight mission. In case of a ground time of 20 minutes after a previous test at negative temperature, this ground time period is not long enough for the battery internal temperature to get closer to the new room temperature. For example, during a flight at -20°C and 70% SOC, the aircraft was on the ground for 10 hours at -20°C and in flight for 3h40 at temperatures between -56°C and -20°C. Once the flight finished, the environmental chamber was set at 20°C to start the next flight. The figure 4-10 shows that the internal temperature of the battery on landing was -33°C and increased by 6°C during the 20 minutes of ground time at 20°C, to reach an end temperature of -26°C. During the next flight, after the first APU start, the battery was disconnected. This failure occurred since the internal temperature of the battery was too low, limiting its performances.

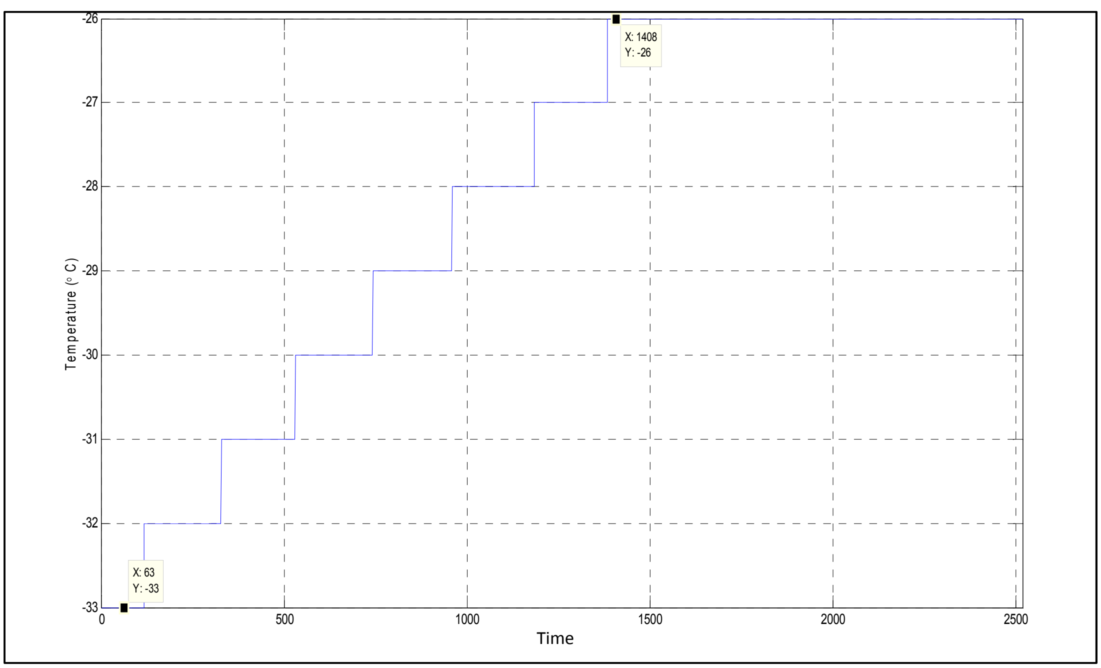

Figure 4-10 Internal temperature during a transit flight of 20 minutes at 20°C
(cycle 1, flight 11)

The figure 4-11 shows an APU start stopped by the BMS at 440A after 3 seconds. When the current peak reached 744A, the battery voltage decreased to 11.89V, with an internal temperature of -26°C. The internal resistance increases significantly when the battery is at a low temperature. Moreover, the SOC was high (80%) and it could not be a reason which generated the voltage drop. This scenario was executed many times but never succeeded. Then, according to the results, when the internal temperature of the battery is below -18°C, it is difficult for the battery to perform three APU starts. Other transit flights with different scenario also did not succeed. More results are available in appendix.

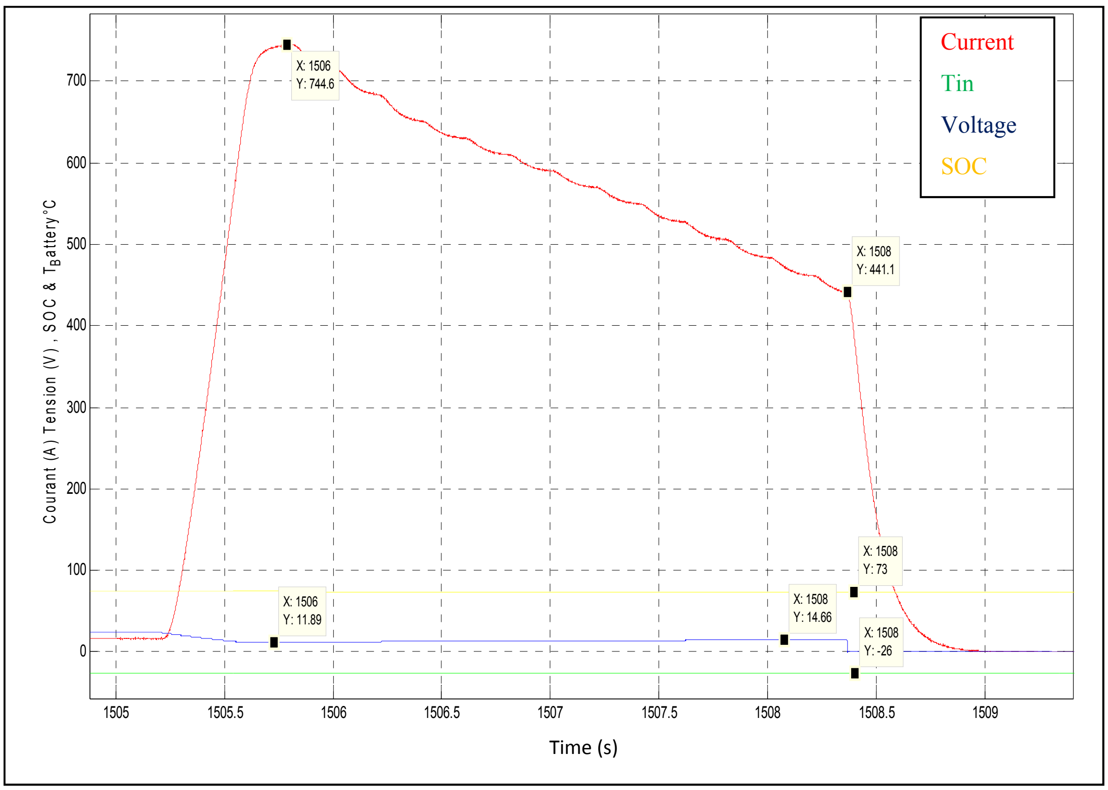

Figure 4-11 Current, voltage, temperature and SOC during an APU start failure (cycle 1, flight 11: -20°C and 80% SOC)

In this test, flight 9 cycle 2, the battery was disconnected during the second APU start, the voltage went down to 0V (see figure 4-12). Before the first current peak, the SOC was at 41% and the internal temperature of the battery was -16°C. If this flight is compared with the flight 11, explained above, a difference of 10°C is observed at the internal temperature (flight 11 cycle 1: T_{in} -26°C, flight 9 cycle 2: T_{in} -16°C) and 40% lower in SOC (flight 11 cycle 1: 80% SOC, flight 9 cycle 2: 40% SOC). The SOC is also an important parameter to observe during an APU start. In this scenario, the low SOC and the cold temperature caused the failure. In the two previously analysed scenarios, the battery is functioning within its limits.

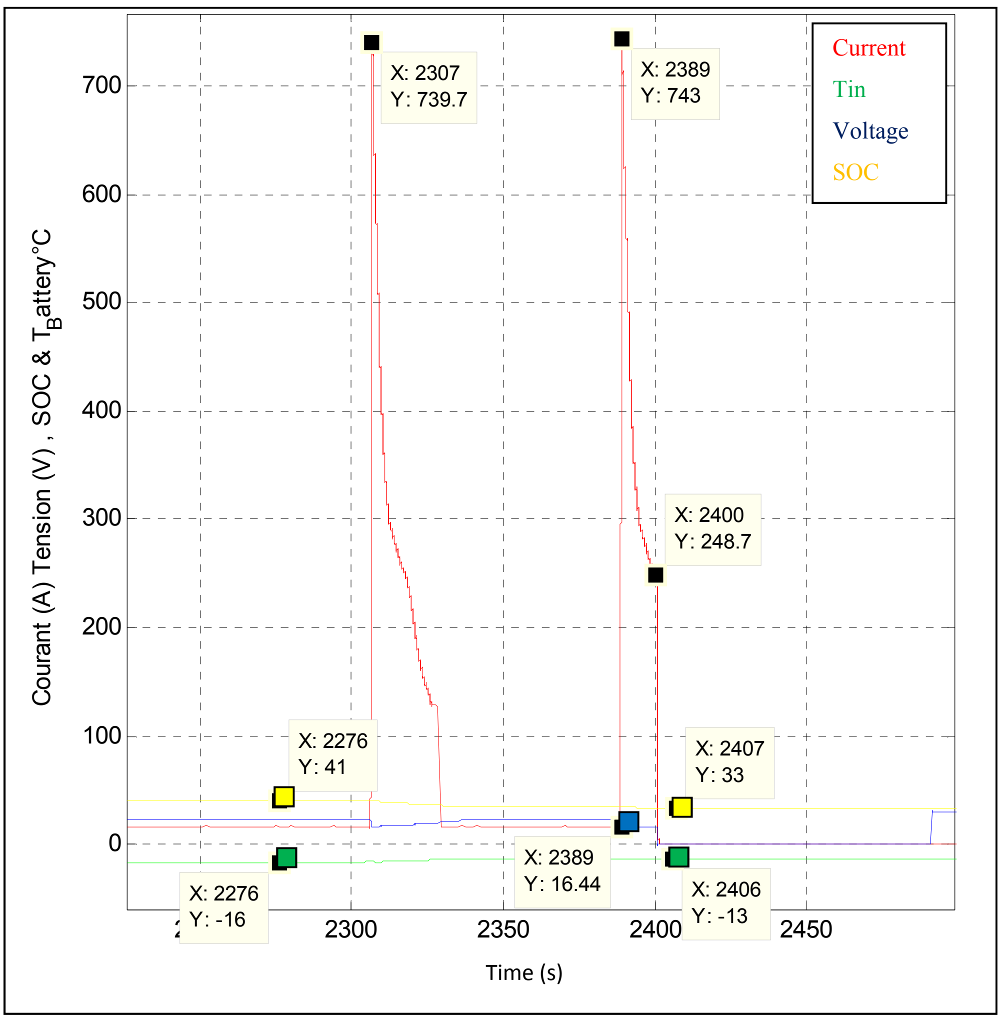

Figure 4-12 Current, voltage, temperature and SOC during an APU start (cycle 2, flight 9)

4.4.2 Temperature alarm

During the tests, the battery S1 was disconnected after spending 10 hours on the ground and performed the three APU starts; with 40% SOC and the surrounding temperature at 50°C (cycle1 flight5). After investigation, it was found that the battery was disconnected by opening its contactor, voltage going down to 0V, when the battery reaches a temperature greater than 45°C. The same test has been simulated with 80% SOC and the internal temperature reached was lower: 42°C. Therefore, it can be assumed that the heat transfer is higher when the state of charge of the battery is low. The BMS algorithm does not allow the operation of the battery when the temperature is higher than 45°C.

In a second step, the S2 battery has been tested. The algorithm of the S2 battery allows its operation until 76°C. However, when the battery stayed on the ground for 10h at 70°C and 80% SOC, it was no longer possible to recharge it after the three APU starts. The recharge was no longer possible since the battery reached 30V (see the circle on the figure 4-13). The BMS prevents the battery from being recharged when the battery voltage is higher than 29V for more than five seconds.

Current peaks at high temperatures significantly increase the internal temperature of the battery. When the internal temperature of the battery is at 70°C, the battery voltage is close to the upper limit and it becomes dangerous to use the battery under these conditions, especially when the battery is being recharged. Risks of exothermic reactions are increased. Therefore the battery can only be discharged at this temperature.

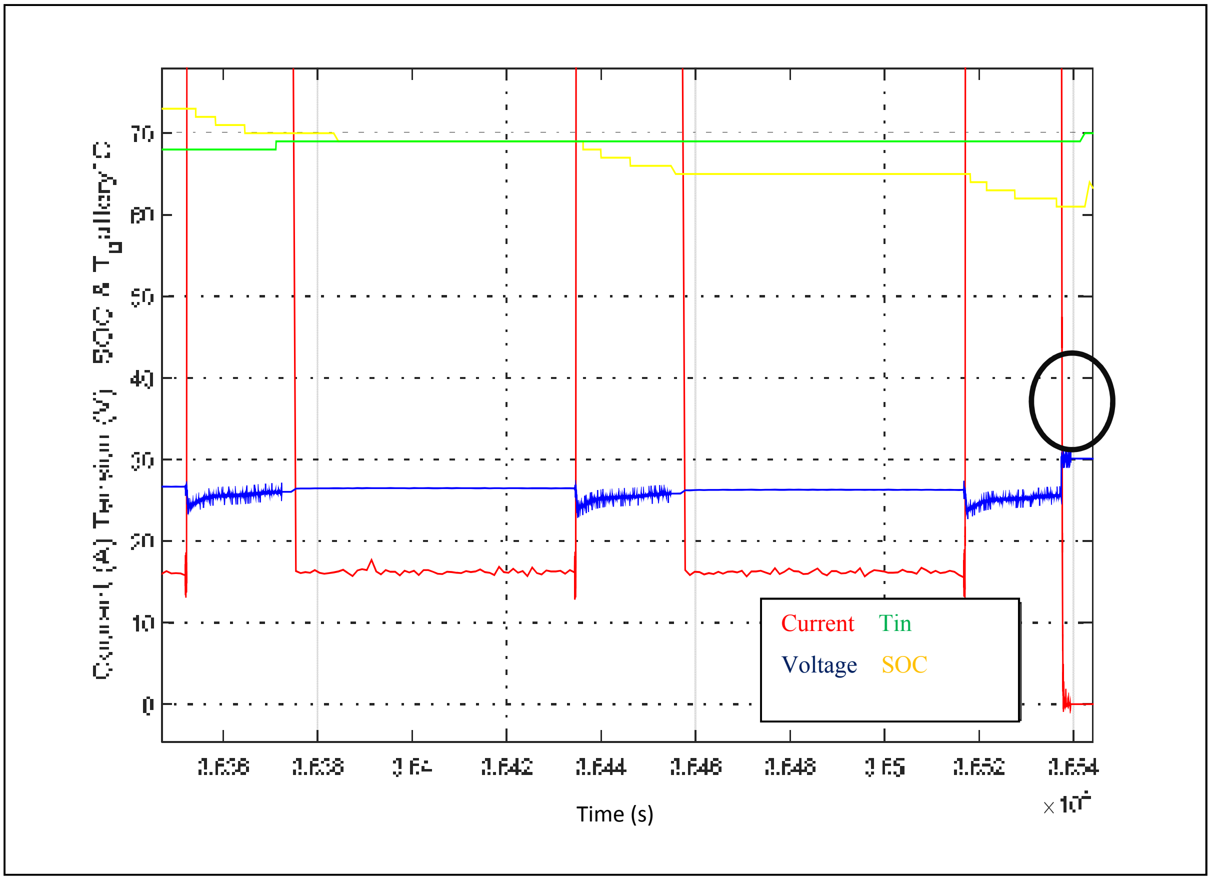

Figure 4-13 Test at 70°C with an SOC at 80%

4.4.3 Low temperature

The operating range of the S1 battery is from -20°C to 30°C and for the S2 battery from -40°C to 70°C.

In tests at -20°C and -40°C, the temperature did not trigger any alarm that prevented the operation of the battery. However, the BMS disconnects the battery when the voltage is too low. During the tests at -20°C, the battery is not able to work properly if the initial SOC is at 40%. For example, during the Cycle 3 Flight 1 (round of tests 1 for the battery S1), the same situation was reproduced as it in the Cycle 1 Flight 1 (10 hours at -20°C with a 40% SOC). However, Cycle 3 Flight 1 did not work. During the third APU, the battery was disconnected at 284A. By analyzing the voltage during the APU starts (figure 4-14), it can be seen that the voltage took longer to increase for the cycle 3. During the third APU, the voltage difference between the two curves was 1.18V before the battery was disconnected.

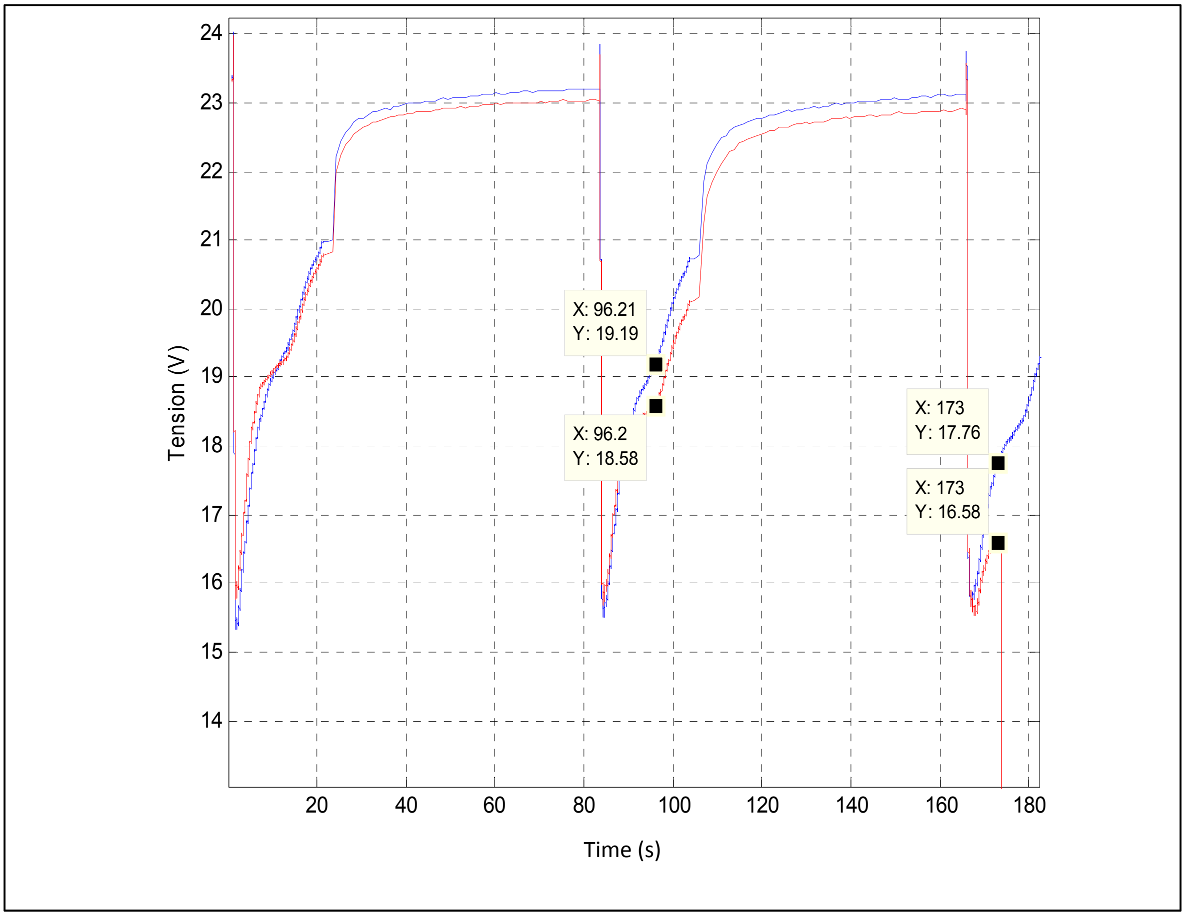

Figure 4-14 Voltage during APU, SOC at 40% and chamber temperature at -20°C
(In blue: cycle 1, flight 1; in red: cycle 3, flight 1)

The BMS disconnects the battery when the voltage drop is significant and the voltage stays too low for a while. When the SOC is at 70%, the temperature limit to performing an APU start is different. In this case, all flights at -20°C and 70% SOC (batteries S1 and S2) succeeded. However, the flights at -40°C did not work. The battery S2 performed tests between -20°C and -40°C, reducing by five degrees each simulation. These tests are designed to determine at which internal temperature the battery S2 is able to perform an APU start (see figure 4-15). The APU starts worked down to -35°C, however, it can be seen that the voltage is very low.

It fell down to 12V, which represents less than 2V per cell. At this temperature, the activity of the cells is reduced. Crystallization of the cell can occur and the risk of depolarization is increased. However, a polarity connector is installed in the battery to reduce the chances of occurrence for this kind of event.

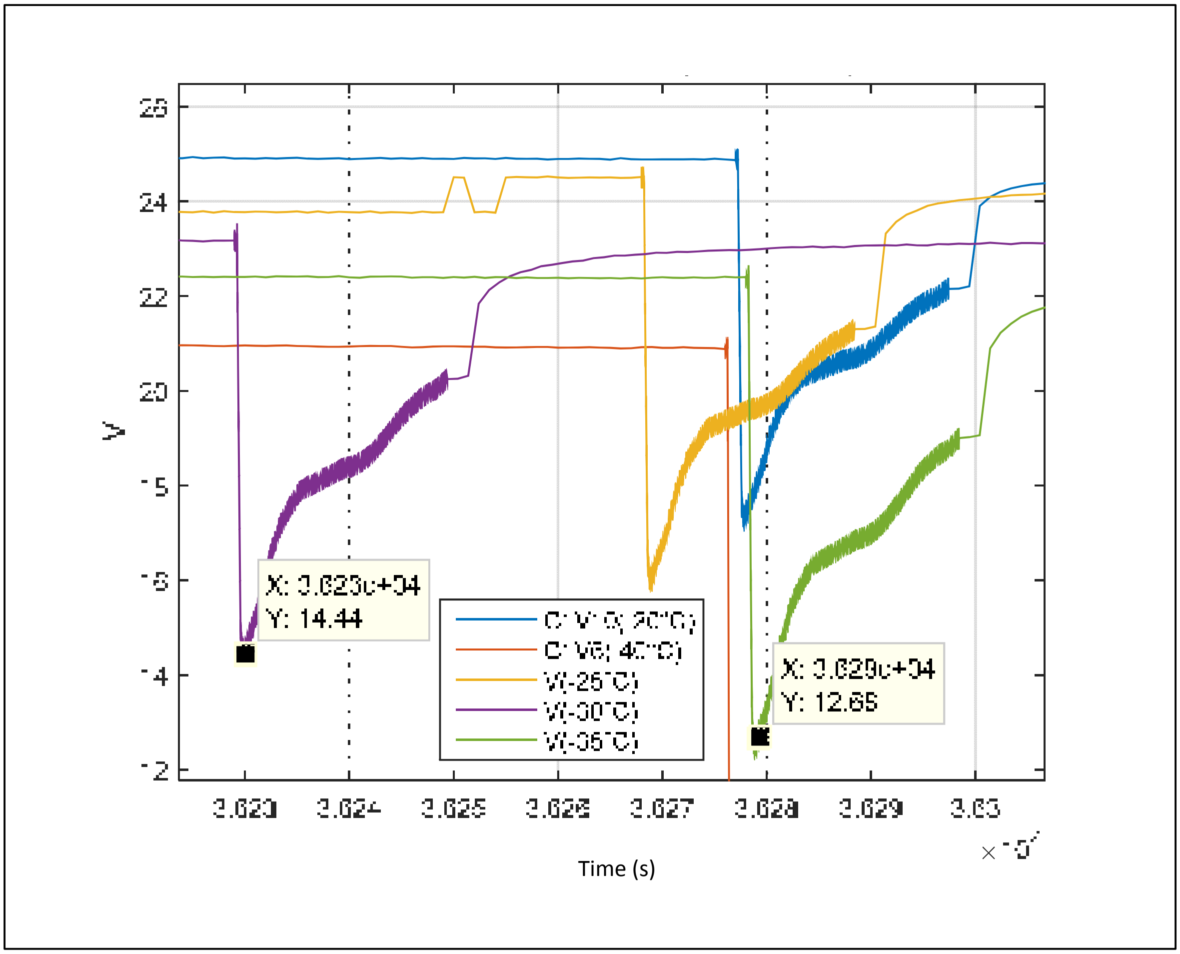

Figure 4-15 Battery voltage during an AP3U start at different temperatures (SOC at 70%)

4.4.4 SOC instability

Battery S2

When the S2 battery tests started, important instability from the SOC have been observed. During the tests, the battery S1 has been replaced by the S2, in order to simulate more flights at higher temperatures (70°C and 50°C). The new BMS configuration, allowed the battery tests up to 70°C and down to -40°C. However, when the tests at negative temperatures were performed, the SOC was unstable and decreases gradually without any current discharged from the battery. Then, when the internal temperature of the battery reached -14°C, the SOC started to gradually increase up to 100% while no recharge current is applied (see figure 4-16, cycle 1 flights 1 and 6 of the battery S2).

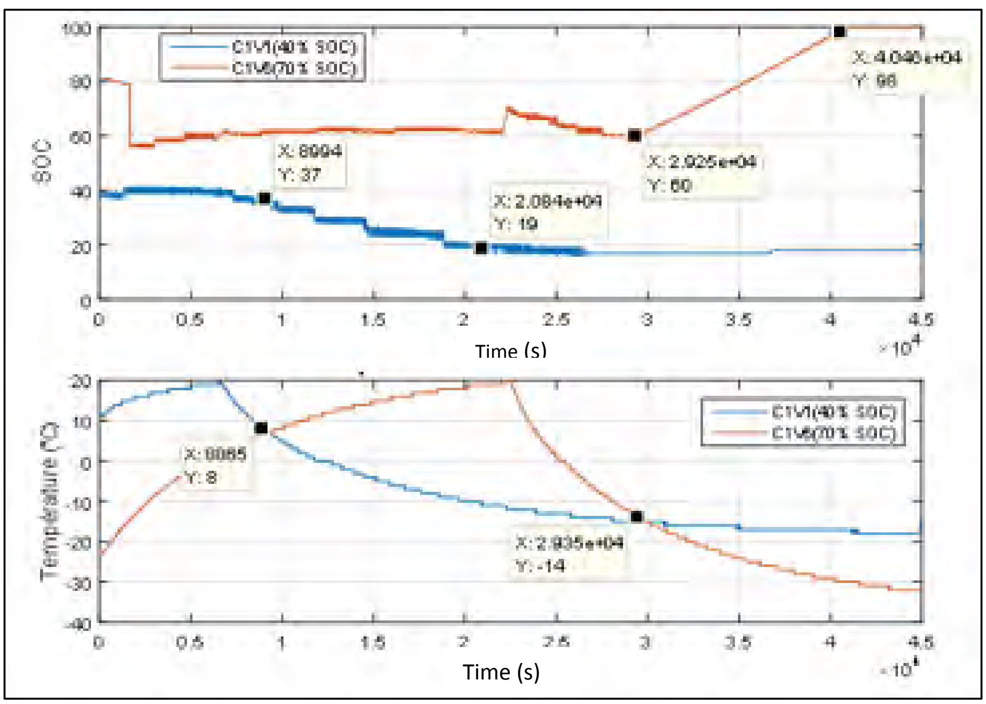

Figure 4-16 SOC unstable – S2 battery

For 40% SOC tests, the SOC decreases so much at the end of the 10 hours on ground at negative temperatures that the battery was disconnected during the first APU start (SOC went below 20%).

Battery S2N

The issue for the S2N is the same as for the S2 battery. The BMS capabilities of estimating the SOC are reduced at negative temperatures and the SOC gradually decreases without any current being applied. Once the internal temperature of the battery reaches -12°C, the SOC starts to gradually increase up to 100%, without any current being applied to recharge the battery. As shows the chart 4-17 (cycle 1 flight 1), the SOC is increasing from 80% up to 100%, while the battery current is at 0A (see right black square on the green line).

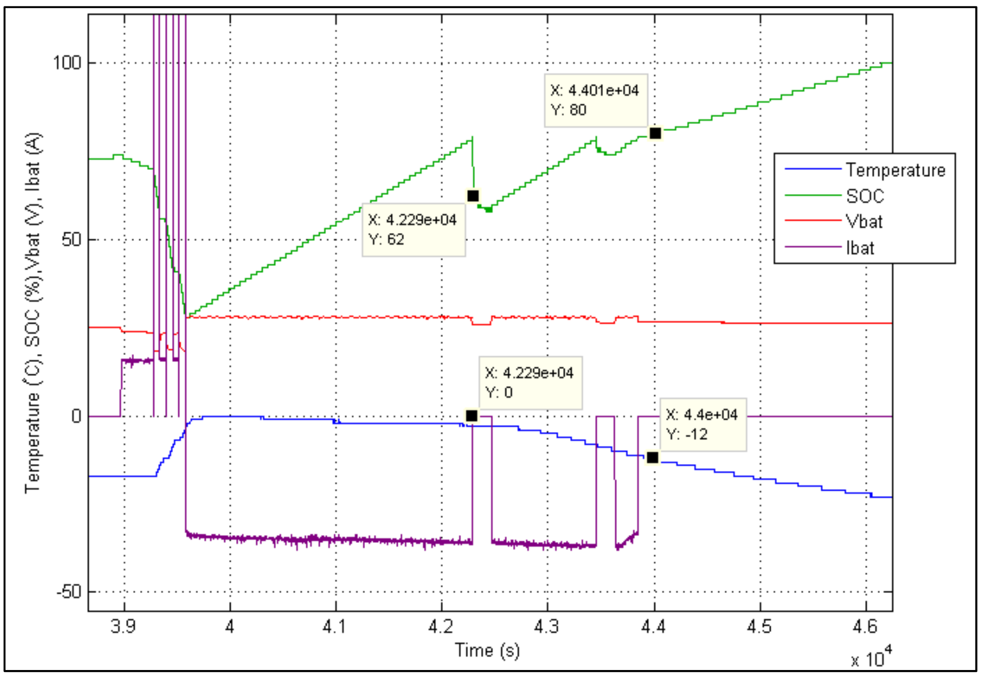

Figure 4-17 Flight sequence at negative temperature (Cycle 1, Flight 1)

It can also be see on the chart 4-17 that, after the three APU starts, the battery is being recharged up to 80% SOC. At the moment the recharge of the battery stopped (no more current), the SOC level dropped by 18% instantly. The SOC level is lowered from 80% to 62%. The algorithm for computing the SOC of the battery seems only to work when a battery current is available and when the internal temperature of the battery is stable and positive.

As shows the chart 4-18, at positive temperatures, there is no drop in SOC when the current is switched off, instead there is a slight increase. While the battery is at positive temperature the SOC is stable. If the temperature is stable the SOC level is more accurate, a temperature variation can corrupt the value of the displayed SOC.

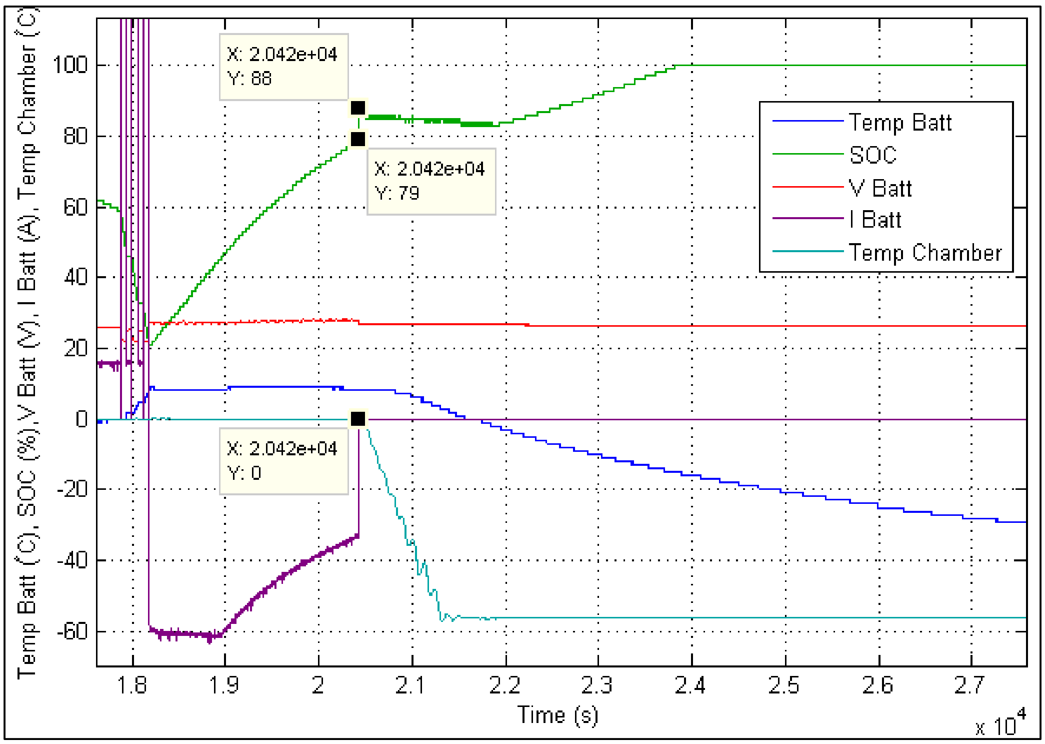

Figure 4-18 Post APU sequence at positive temperature (Cycle 1 Flight 2)

The chart 4-19 presents the ground phase of a flight at -20°C. The chart displays the instability of the SOC level. The current is at 0A and the voltage is stable during the complete ground phase. Firstly, the SOC is going down from 65% to 46%. At 46% the battery reaches an internal temperature of -14°C, and then, the SOC starts to increase again to reach 73% at the end of the ground phase period.

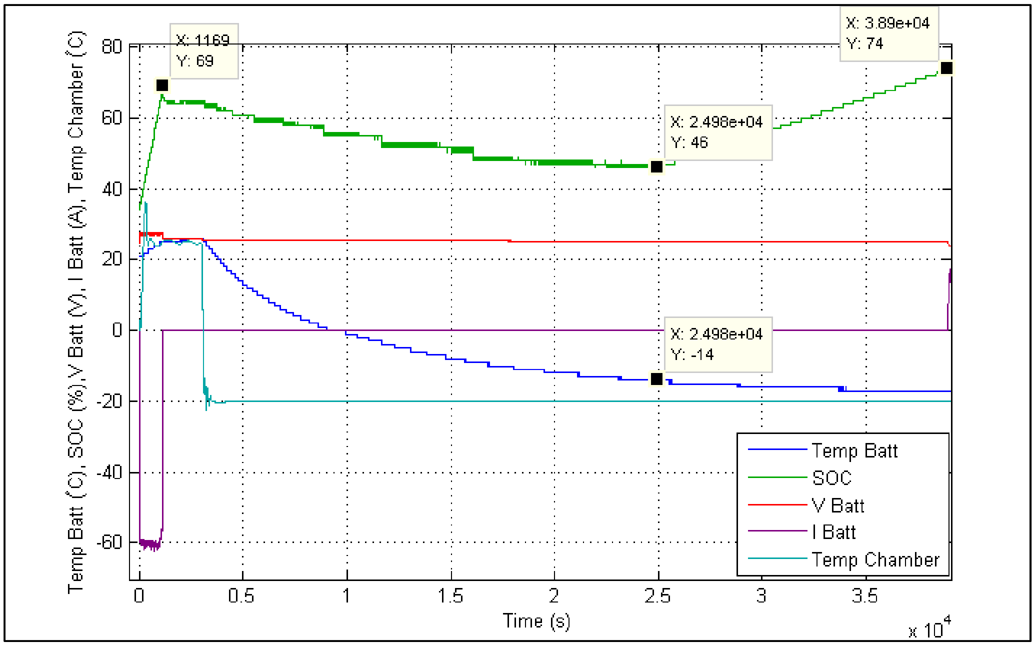

Figure 4-19 Ground phase of 10h at negative temperatures (Cycle 1 Flight 1)

On the other hand, as shown in the chart 4-20, the SOC is stable when the internal temperature of the battery is positive. The internal temperature of the battery is also stable during this phase. The ground phase temperature for this test was 20°C.

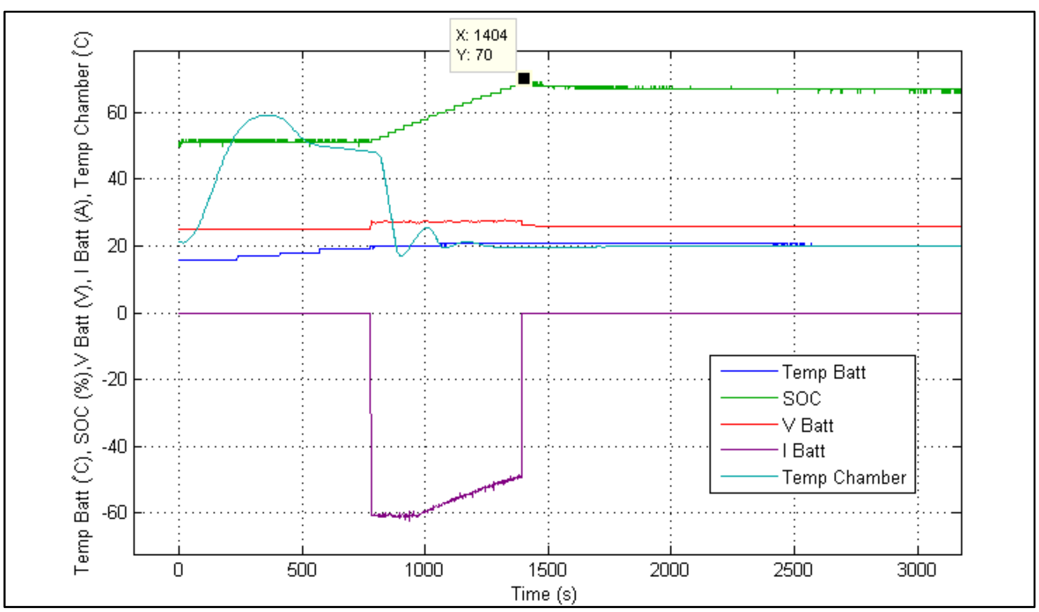

Figure 4-20 Ground phase of 10h at positive temperatures (Cycle 2 Flight 2)

4.4.5 SOC reliability test

With the S2N battery a SOC reliability test has been carried out. During this test, only the temperature was changing, so as to observe the evolution of the SOC at different temperatures. As shows the table 4-4, the SOC is changing with the change in the negative temperature. This means the SOC algorithm is directly influenced by the external temperature, therefore the real amount of energy remaining in the battery is never known at negative temperatures.

Table 4-4 SOC reliability test

Temperature (°C)	SOC (%)
-20	100
-6	33
1	38

4.4.6 Behaviour comparison

This section will presents the behavioural differences between the Li-Ion S1, S2 and S2N batteries. The S1 battery can be recharged at any temperature but its operating range is smaller than the one for the batteries S2 and S2N. The operating range of the S1 battery is from -20°C to 30°C. For the negatives temperatures during the tests, the batteries S2 and S2N had to be warmed to 25°C before proceeding to the adjustment of the SOC. For the hot temperatures, the battery can be recharged at any temperature e.g. at 50°C the SOC can be changed at this temperature without waiting for the internal temperature of battery to be at 25°C.

The performances of the batteries S2 and S2N are almost the same with the exception that the battery S2N needs to be recharged directly after the 3rd APU, otherwise the battery is disconnected. For the battery S2, it is possible to wait 30 minutes after the third APU in order for the battery to stabilise its temperature and equalize its cells.

4.5 Temperature results

During the battery S1 testing, 271 flights were performed, 36 of them failed. For the battery S2, 35 flights were performed, 14 of them failed. For the battery S2N, 15 flights were carried out, 7 of them failed.

4.5.1 Test at -40°C

Battery S1

It does not work at this temperature.

Battery S2

No flight has succeeded at this temperature. The internal temperature of the battery is too low; after spending 10 hours at -40°C it reaches -36°C.

Battery S2N

None of the flights at this temperature have succeeded for the S2N. Only flights with 70% SOC have been tested. The battery also reached -36°C after 10h on the ground. The battery failure happened during the first APU start, the current only reaches 250A-300A of the new APU curve. At the moment the failure occurs, the battery is disconnected and the voltage drops to 0V.

4.5.2 Test at -20°C

Battery S1 & S2

At this temperature there are two factors to consider. The time spent on the ground and the SOC level of the battery. Firstly, if the battery is recharged at 70% or more and spends 10 hours of cold soaking at -20°C, the system works properly. Secondly, if the battery is at 40% SOC and spent 10 hours cold soaked at -20°C, the APU start is not safe to operate. These parameters (-20°C for 10h with 40% SOC) represents the operating limits for the battery S1. Moreover, the SOC of the battery S2 was much more unstable, it could fall below 20%. This generates an alarm which prevents the system from operating. Thirdly, if the aircraft is in transit step (20min on the ground) after the execution of typical flight (3h40 at -56°C), the battery is not able to provide enough energy to start the APU. The internal temperature of the battery is too low.

Battery S2N

For the S2N battery, only tests at 70% and 90% SOC have been carried out. For the tests at -20°C and 70% SOC, three of them have failed after they successfully passed three APU starts (Cycle 1 flight 4, Cycle 2 flight 3 and Cycle 2 flight 4). As shown the chart 4-21, after the 3rd APU start, the battery has been disconnected. The scenarios -20°C and 70% were again simulated (in flight 7 of the cycle 2 and in flights 3, 4 and 6 of the cycle 3), with a modification in the program for recharging the battery on completion of the three APU starts (no more waiting time of 30 minutes). This time, the battery was not disconnected and the flights succeeded.

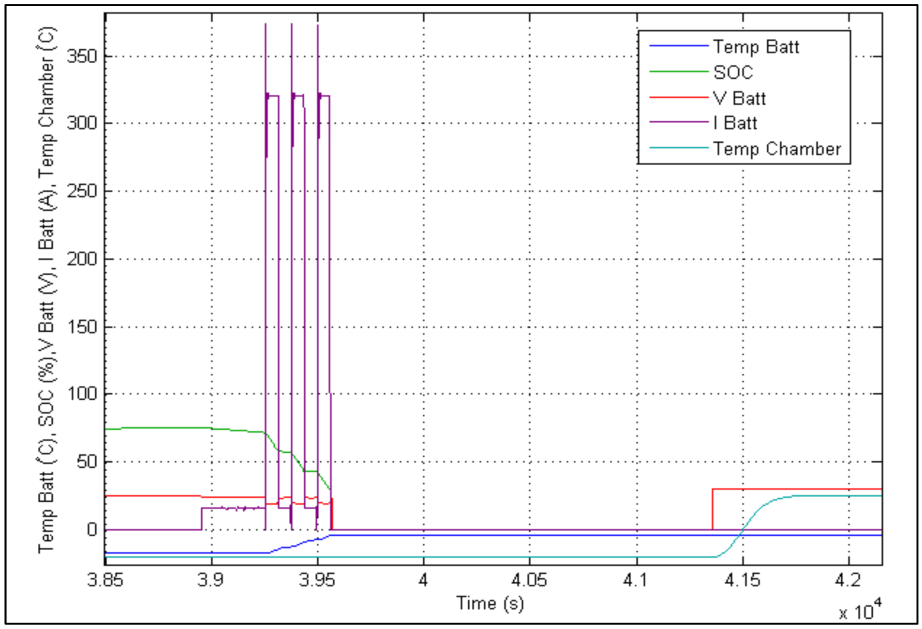

Figure 4-21 Communication lost after three successful APU starts
(S2N Cycle 1 Flight 4)

4.5.3 Test between 0°C and 50°C

At these temperatures the batteries had no problem to start the APU. All flights were successful despite the different SOC levels. However, for the battery S1, testing at 50°C did not work. The BMS algorithm prevented the battery operation when the internal temperature of the battery reaches 45°C. With the battery S2, tests have been carried out at 50°C at different SOC and no problem occurred. For the S2N, the tested flights at 0°C and 20°C were also successful.

4.5.4 Test at 70°C

Only two flights have been simulated at this temperature. However, none of them worked properly. Each time the battery was able to successfully pass the 3 APU starts, the voltage increased until a value greater than 29V for more than five seconds. The BMS considers the cells overcharged and does not allow the system to recharge. Therefore the battery can’t be recharged to 80% before the flight sequence.

4.6 Recommendations

According to the results of the tests carried out, it has been noticed that some elements would require more attention for a faster deployment of the Li-Ion battery in the aeronautical industry. Therefore, the following suggestions list has been made:

- Improvement of the SOC calculation system to be fully operational at temperatures below 0°C or find a device/method to always keep the battery above the freezing point;
- Add a 20min rest period after the three APU starts. Therefore, the battery will have time to equalize its cells before being recharged and will be able to display a more accurate SOC. This step is not possible on the S2N, otherwise the battery will lose the connection;
- Add a heating device around the battery, thus the battery will never be too cold to start an APU. Since, after a flight at -56°C followed by a transition period of only 20min on the ground, the battery does not have the time to sufficiently heat up to start an APU;
- Test the batteries at different atmospheric pressures to check if the performances are still the same.

4.7 Conclusion

During the flight simulations, the S1 battery has executed 271 flights, 235 were successful and 36 failed. As for the S2 battery, 35 flights were performed, 14 of them failed. For the S2N battery, 15 flights were carried out, 7 of them failed.

According to the user manual, the battery is designed to operate from -18°C and +71°C. According to the tests carried out, the battery was able to perform an APU start with an internal temperature at -35°C if the SOC is greater than or equal to 70%. However, when the battery has an SOC of 40%, its temperature operating range is smaller, between 0°C and 50°C only. The batteries are not working at -40°C. With the S2 battery, the system was able to perform the APU starts with an internal temperature of 69°C, however it was impossible to recharge the battery after the APU starts.

At negatives temperatures, for the S2 and S2N batteries, the algorithm computing the SOC is not working properly. The SOC is continuously changing. The battery is not being recharged or discharged while the SOC is increasing or decreasing at negatives temperatures.

Despite all the tests, the batteries S1, S2 and S2N did not show any signs of danger. Each time the battery was tested outside of its limits, the BMS activated an alarm. The battery has multiple protection devices to exclude any risk of damage.

CHAPTER 5

COMPARATIVE PERFORMANCE ANALYSIS OF LI-ION AND NI-CD BATTERIES

5.1 Introduction

In this chapter only the flights from the Li-Ion S1, Li-Ion S2 and Ni-Cd are compared. The S2N is using another APU curve, therefore the battery behaviour differ.

5.2 Flight results at different temperatures

5.2.1 Flight at -40°C

Table 5-1 Flight results at -40°C

SOC	Battery	Result	APU Max Current	APU Min Voltage	Battery temp during APU	Details
40%	Li-Ion S1	-	-	-	-	-
	Li-Ion S2	Failure: current and voltage	340A	-1.2V	-35°C	Failure 1st APU
	Ni-Cd	Failure: current and voltage	425A	0.2V	-33°C	Failure 1st APU
70%	Li-Ion S1	-	-	-	-	-
	Li-Ion S2	Failure: current and voltage	340-385A	-1.1V	-35°C	Failure 1st APU
	Ni-Cd	Failure: voltage Success: current	750-800A	1.5-2.7V	-34°C	Failure 1st APU

Li-Ion S1: No flights have been executed since it was outside the operating range of the battery. The Operating range of the S1 battery is from -20°C to 30°C.

Li-Ion S2: 8 flights have been tested at -40°C. No flights have succeeded at this temperature.

Ni-Cd: 5 flights have been tested at-40°C. No flights have succeeded at this temperature.

5.2.2 Flight at -35°C, -30°C and -25°C

Table 5-2 Flight results at -35°C, -30°C and -25°C

Temperature	SOC	Battery	Result	APU Max Current	APU Min Voltage	Battery temp during APU
-35°C	70%	Li-Ion S1	-	-	-	-
		Li-Ion S2	Success: current and voltage	745A	12.4V	-31°C
		Ni-Cd	-	-	-	-
-30°C	70%	Li-Ion S1	-	-	-	-
		Li-Ion S2	Success: current and voltage	745A	14.3V	-27°C
		Ni-Cd	-	-	-	-
-25°C	70%	Li-Ion S1	-	-	-	-
		Li-Ion S2	Success: current and voltage	745A	15.9V	-22°C
		Ni-Cd	-	-	-	-

Li-Ion S1: No flights have been executed at these temperatures.

Li-Ion S2: For each temperature 1 flight has been tested at 70% SOC.

Ni-Cd: No flights have been executed at these temperatures.

5.2.3 Flight at -20°C

Table 5-3 Flight results at -20°C

SOC	Battery	Result	APU Max Current	APU Min Voltage	Battery temp during APU	Details
40%	Li-Ion S1	Failure: voltage for some flights Success: current	745A	Failure: -1.1V Success: 16.3-19.7V	Failure: -16°C Success: -2°C	Failure 1st, 2nd or 3rd APU
	Li-Ion S2	Failure: voltage for some flights. Current for one flight only Success: current	Failure: 50A Success: 745A	Failure: -1.1V Success: 21.6-22.5V	Failure: -17°C Success: 12°C	Failure 1st APU
	Ni-Cd	Failure: voltage. Current for some flights Success: current	Failure: 20-340A Success: 745-790A	0.01-4.3V	-18°C or 25°C	Failure 1st or 2nd APU
70%	Li-Ion S1	Success: current and voltage	745A	16-17.2V	-18°C	
	Li-Ion S2	Success: current and voltage Failure: voltage for some flights	745A	17.3-18.3V	-18°C	Low voltage after the completion of the APU starts. Then flights successfully passed. One test failed with overvoltage after APU starts.

SOC	Battery	Result	APU	APU Min	Battery	Details

			Max Current	Voltage	temp during APU	
70%	Ni-Cd	Failure: voltage Success: current	745-800A	9.5-11.9V	-18°C	Failure 2nd or 3rd APU
90%	Li-Ion S1	Success: current and voltage	745A	17.4-17.7V	-19°C	
	Li-Ion S2	Success: current and voltage	745A	23.4V	14°C	
	Ni-Cd	Success: current and voltage	745A	17V	18°C	

Li-Ion S1: 49 flights have been tested at -20°C.

Li-Ion S2: 13 flights have been tested at -20°C.

Ni-Cd: 10 flights have been tested at -20°C.

5.2.4 Flight at 0°C

Table 5-4 Flight results at 0°C

SOC	Battery	Result	APU Max Current	APU Min Voltage	Battery temp during APU	Details
40%	Li-Ion S1	Success: current and voltage	745A	19.3-20.5V	0-2°C	
	Li-Ion S2	-	-	-	-	
	Ni-Cd	-	-	-	-	
70%	Li-Ion S1	Success: current and voltage	745A	20.2-21.4V	0°C	
	Li-Ion S2	-	-	-	-	
	Ni-Cd	Success: current and voltage	745A	15.1V	2°C	
80%	Li-Ion S1	Success: current and voltage	745A	15.3-22.3V	From -14°C to 12°C	Temperature difference is that wide because of the 20min ground time
	Li-Ion S2	Success: current and voltage	745A	22.6V	0°C	
	Ni-Cd	Failure: voltage Success: current	745A	10.9V	-20°C	Almost succeeded. Failure because of internal temperature

SOC	Battery	Result	APU Max Current	APU Min Voltage	Battery temp during APU	Details
90%	Li-Ion S1	Success: current and voltage	745A	20-20.8V	0°C	
	Li-Ion S2	Success: current and voltage	745A	21.6V	0°C	
	Ni-Cd	Success: current and voltage	800A	16.8V	1°C	

Li-Ion S1: 54 flights have been tested at 0°C.

Li-Ion S2: 2 flights have been tested at 0°C.

Ni-Cd: 3 flights have been tested at 0°C

5.2.5 Flight at 20°C

Table 5-5 Flight results at 20°C

SOC	Battery	Result	APU Max Current	APU Min Voltage	Battery temp during APU	Details
40%	Li-Ion S1	Failure: voltage, one flight only Success: current and voltage	745A	Failure: -0.9V Success: 17.6 to 20.5V	Failure: -14°C Success: -10°C to 5°C	One flight failure 3rd APU. All other flights succeeded
	Li-Ion S2	-	-	-	-	
	Ni-Cd	-	-	-	-	
70%	Li-Ion S1	Success: current and voltage	745A	15.1 to 22.5V	-20°C to 20°C	
	Li-Ion S2	Success: current and voltage	745A	22.6V	20°C	
	Ni-Cd	Success: current and voltage	800A	16.8V	24°C	
80%	Li-Ion S1	Failure: voltage, some flights only Success: current	745A	Failure: -1.2V Success: 16 to 22.7V	Failure: -26°C Success: -20°C to 25°C	Failure 1st APU
	Li-Ion S2	-	-	-	-	
	Ni-Cd	-	-	-	-	
90%	Li-Ion S1	Success: current and voltage	745A	19-23.4V	-10°C to 20°C	
	Li-Ion S2	-	-	-	-	
	Ni-Cd	-	-	-	-	

Li-Ion S1: 97 flights have been tested at 20°C.

Li-Ion S2: 1 flight has been tested at 20°C.

Ni-Cd: 1 flight has been tested at 20°C.

5.2.6 Flight at 30°C

Table 5-6 Flight results at 30°C

SOC	Battery	Result	APU Max Current	APU Min Voltage	Battery temp during APU	Details
40%	Li-Ion S1	Failure: voltage, some flights only Success: current	745A	Failure: -0.4V to -1.7V Success: 17.1V to 21.4V	Failure: -3°C to -15°C Success: -14°C to 30°C	Failure 1st, 2nd or 3rd APU
	Li-Ion S2	-	-	-	-	
	Ni-Cd	-	-	-	-	
70%	Li-Ion S1	Success: current and voltage	745A	21.2V to 22.1V	30°C	
	Li-Ion S2	Success: current and voltage	745A	22.6V	30°C	
	Ni-Cd	Success: current and voltage	790A	17.75	30°C	
80%	Li-Ion S1	Failure: voltage, some flights only Success: current	745A	Failure: -1.1V to -2V Success: 17.4-23.1V	Failure: -24°C Success: -14°C to 30°C	Failure 1st APU
	Li-Ion S2	-	-	-	-	
	Ni-Cd	-	-	-	-	

SOC	Battery	Result	APU	APU Min	Battery temp	Details

			Max Current	Voltage	during APU	
90%	Li-Ion S1	Success: current and voltage	745A	19.8-23.6V	-8°C to 30°C	
	Li-Ion S2	Success: current and voltage	745A	23.8V	30°C	
	Ni-Cd	Success: current and voltage	800A	18.1V	30°C	

Li-Ion S1: 69 flights have been tested at 30°C.

Li-Ion S2: 2 flights have been tested at 30°C.

Ni-Cd: 2 flights have been tested at 30°C.

5.2.7 Flight at 50°C

Table 5-7 Flight results at 50°C

SOC	Battery	Result	APU Max Current	APU Min Voltage	Battery temp during APU	Details
40%	Li-Ion S1	Success: current and voltage Failure: voltage after APU	765A	21V	50°C	Failure after APU, cell overcharged (>30V)
	Li-Ion S2	Success: current and voltage	745A	21.8V	50°C	
	Ni-Cd	Success: current and voltage	800A	15.3V	52°C	
80%	Li-Ion S1	Success: current and voltage	765A	22.7V	50°C	
	Li-Ion S2	Success: current and voltage	745A	23.5V	50°C	
	Ni-Cd	Success: current and voltage	745-800A	17.4-18V	50°C	
90%	Li-Ion S1	-	-	-	-	
	Li-Ion S2	Success: current and voltage	745A	24.1V	50°C	
	Ni-Cd	Success: current and voltage	745-800A	17.9-18.1V	25-50°C	

Li-Ion S1: 2 flights have been tested at 50°C.

Li-Ion S2: 4 flights have been tested at 50°C.

Ni-Cd: 8 flights have been tested at 50°C.

5.2.8 Flight at 70°C

Table 5-8 Flight results at 70°C

SOC	Battery	Result	APU Max Current	APU Min Voltage	Battery temp during APU	Details
40%	Li-Ion S1	-	-	-	-	
	Li-Ion S2	Success: current and voltage Failure: voltage after APU	745A	23.3V	70°C	Failure after 3rd APU, cell overcharged (>30V)
	Ni-Cd	Success: current Failure: voltage	750A	8.7V	71°C	Failure 3rd APU
70%	Li-Ion S1	-	-	-	-	
	Li-Ion S2	-	-	-	-	
	Ni-Cd	Success: current and voltage	745A	17.4V	70°C	
80%	Li-Ion S1	-	-	-	-	
	Li-Ion S2	Success: current and voltage Failure: voltage after APU	745A	23.6V	70°C	Failure after 3rd APU, cell overcharged (>30V)
	Ni-Cd	Success: current and voltage	745A	17.7V	72°C	

Li-Ion S1: No flights have been executed since it was outside the operating range of the battery.

Li-Ion S2: 2 flights have been tested at 70°C.

Ni-Cd: 3 flights have been tested at 70°C.

5.2.9 Summary of the flight results at different temperatures

Table 5-9 Flight results at different temperatures

Temperature	SOC	Li-Ion S1 Current	Li-Ion S1 Voltage	Li-Ion S2 Current	Li-Ion S2 Voltage	Ni-Cd Current	Ni-Cd Voltage
-40°C	40%	-	-	Failure	Failure	Failure	Failure
	70%	-	-	Failure	Failure	Success	Failure
-35°C	70%	-	-	Success	Success	-	-
-30°C	70%	-	-	Success	Success	-	-
-25°C	70%	-	-	Success	Success	-	-
-20°C	40%	Success	Success/ Failure	Success/ Failure	Success/ Failure	Success/ Failure	Failure
	70%	Success	Success	Success	Success/ Failure	Success	Failure
	90%	Success	Success	Success	Success	Success	Success
0°C	40%	Success	Success	-	-	-	-
	70%	Success	Success	-	-	Success	Success
	80%	Success	Success	Success	Success	Success	Failure
	90%	Success	Success	Success	Success	Success	Success
20°C	40%	Success	Success/ Failure	-	-	-	-
	70%	Success	Success	Success	Success	Success	Success
	80%	Success	Success/ Failure	-	-	-	-
	90%	Success	Success	-	-	-	-
30°C	40%	Success	Success/ Failure	-	-	-	-
	70%	Success	Success	Success	Success	Success	Success
	80%	Success	Success/ Failure	-	-	-	-
	90%	Success	Success	Success	Success	Success	Success
50°C	40%	Success	Success/ Failure	Success	Success	Success	Success
	80%	Success	Success	Success	Success	Success	Success
	90%	-	-	Success	Success	Success	Success
70°C	40%	-	-	Success	Failure	Success	Failure
	70%	-	-	-	-	Success	Success
	80%	-	-	Success	Failure	Success	Success

In the table 5-9, among the columns current and voltage a failure means the value is below the minimum threshold, therefore leading the test to a failure. A success means the value is above the minimum threshold. See the previous chapter for more details on each result presented in the table 5-9 and the specific chapter about the Li-Ion or Ni-Cd.

In the table 5-9, if a result may seems unusual or unexpected, please check the specific chapter related to the specific battery. For these results, the main reason is often the temperature because there is a big gap between the internal temperature and the surrounding temperature, therefore altering the battery performances. For example, the surrounding temperature is at 0°C but the internal temperature of the battery is at -20°C (Ni-Cd: 80% SOC at 0°C).

5.3 Observations

5.3.1 Temperature influence on the voltage

The table 5-10 displays the batteries voltage at different temperatures with 70% SOC. The values were taken at the end of the 10h period on the ground. The Li-Ion voltage had a lot of noise in its data, therefore a moving average filter has been used to smooth the voltage curve to obtain more readable data, see graph 5-1. As a reminder, the nominal voltage of the Li-Ion is 25V and for the Ni-Cd 24V.

Table 5-10 Battery voltage at different temperatures (SOC at 70%)

Temperature	Li-Ion S1	Li-Ion S2	Ni-Cd
-40°C	-	25.96V	26.3V
-35°C	-	25.97V	-
-30°C	-	26.1V	-
-25°C	-	26.18V	-
-20°C	25.95V	26.2V	26.32V
0°C	26.74V	-	26.01V
20°C	26.72V	26.89V	25.91V
30°C	26.71V	26.76V	26.11V
70°C	-	-	25.3V

As shows the table 5-11, the voltage difference between two temperatures is lower for the Ni-Cad compared to the Li-Ion.

Table 5-11 : Voltage difference between two temperatures for each battery

Voltage difference between:	Li-Ion S1	Li-Ion S2	Ni-Cd
-40°C & 20°C	-	0.93V	0.39V
-20°C & 20°C	0.77V	0.69V	0.41V

The graph 5-1 shows the voltage measurement of the Li-Ion S1. By zooming in, it can be seen that the measurement is corrupted by some noise, therefore a moving average filter has been used to smooth the voltage curve. The yellow line represents the result of the filtered signal. The flight conditions were 70% SOC and -20°C.

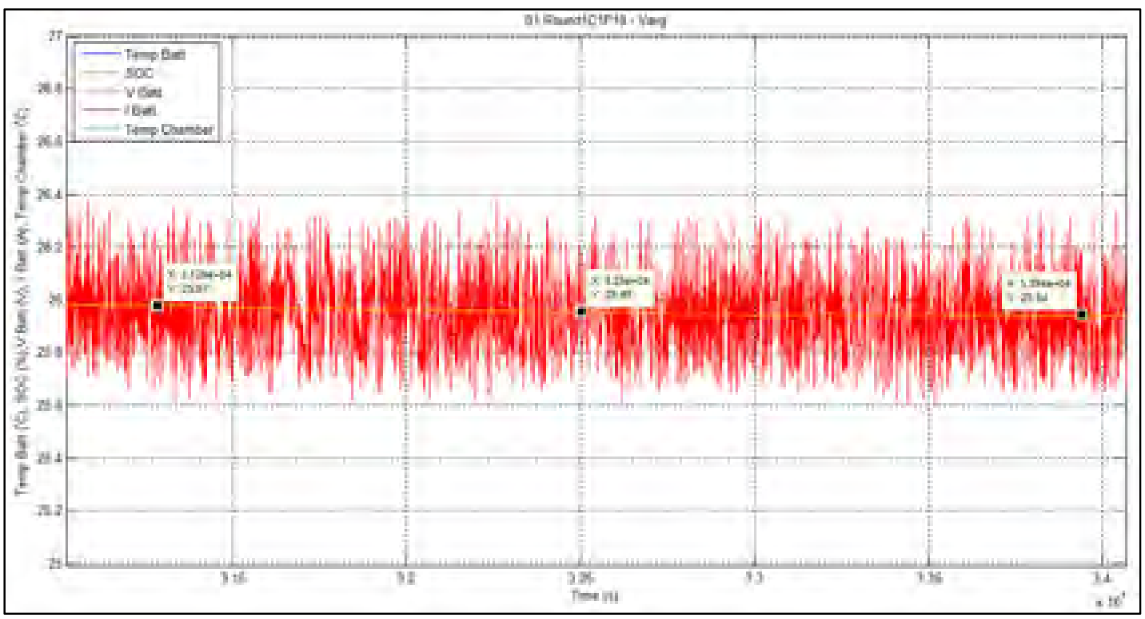

Figure 5-1 Moving average filter applied to the voltage measurement (Li-Ion S1)

5.3.2 Temperature influence on the voltage during the APU starts

The table 5-12 displays the batteries minimum voltage during the APU starts at different temperatures with 70% SOC. The data show a voltage increase with the increase of the temperature. The table 5-12 also shows a higher minimum voltage during the APU for the Li-Ion compared to the Ni-Cd for the same test conditions. As a reminder, the nominal voltage of the Li-Ion is 25V and for the Ni-Cd 24V.

Table 5-12 Voltage during the APU starts at different temperatures (SOC at 70%)

Temperature	Li-Ion S1 Minimum voltage	Li-Ion S1 % nominal voltage	Li-Ion S2 Minimum voltage	Li-Ion S2 % nominal voltage	Ni-Cd Minimum voltage	Ni-Cd % nominal voltage
-40°C	-	-	-1V	-4	1.9V	7.9
-35°C	-	-	12.4V	49.6	-	-
-30°C	-	-	14.3V	57.2	-	-
-25°C	-	-	15.9V	63.6	-	-
-20°C	16V	64	17.5V	70	11V	45.8
0°C	21V	84	-	-	15.1V	62.9
20°C	22V	88	22.6V	90.4	16.8V	70
30°C	22.1V	88.4	22.6V	90.4	17.7V	73.8
70°C	-	-	-	-	17.4V	72.5

5.3.3 SOC influence on the voltage during the APU starts

The table 5-13 displays the battery minimum voltage at different SOC level during the APU starts with a temperature of 30°C. According to the tests, the higher the SOC, the higher the voltage during the APU starts. The voltage at different SOC stays closer to its nominal value for the Li-Ion compared to the Ni-Cd. As a reminder, the nominal voltage of the Li-Ion is 25V and for the Ni-Cd 24V.

Table 5-13 Voltage during the APU starts at different SOC (Temperature at 30°C)

SOC	Li-Ion S1 Minimum voltage	Li-Ion S1 % nominal voltage	Li-Ion S2 Minimum voltage	Li-Ion S2 % nominal voltage	Ni-Cd Minimum voltage	Ni-Cd % nominal voltage
40%	21.2V	84.8	-	-	-	-
70%	22.1V	88.4	22.6V	90.4	17.7V	73.75
80%	22.8V	91.2	-	-	-	-
90%	23.2V	92.8	23.8V	95.2	18.1V	75.42

5.4 Ground phase of 20 minutes

During the ground phase, the aircraft can stay on the ground for 20 minutes or 10 hours at a designated temperature. Therefore, when the aircraft is staying on the ground only for 20min at a new surrounding temperature, the internal temperature of the battery does not have the time to significantly change. For example, with the Ni-Cd, during the cycle 3 flight 10, the internal temperature of the battery was at 22.6°C at the beginning of the 20min period on the ground and at 16.3°C at the end, while the surrounding temperature was at -20°C. Thus, it can be observed that during this short period of time, the battery has only decreased its internal temperature by 6.3°C.

The table 5-14 presents the results of the tests with a ground phase of 20 minutes. Among the columns current and voltage a failure means the value is below the minimum threshold. A success means the value is above the minimum threshold. The main cause of test failure in these conditions is the voltage for both types of battery. The Li-Ion and the Ni-Cd have more difficulties to perform three consecutive APU starts with a SOC of 40%.

Table 5-14 Flight results at different SOC with a ground phase of 20 minutes

SOC	Li-Ion S1 Current	Li-Ion S1 Voltage	Li-Ion S2 Current	Li-Ion S2 Voltage	Ni-Cd Current	Ni-Cd Voltage
40%	Success	Success /Failure	Success	Success/ Failure	Success/ Failure	Failure
70%	Success	Success	-	-	-	-
80%	Success	Success /Failure	-	-	Success	Failure
90%	Success	Success	Success	Success	Success	Success

The main point to remember in this chapter is, in real conditions, after a flight at -56°C the internal temperature of the battery will only increase by 6°C on average while staying on the ground for only 20min. Therefore, the battery can have difficulties to conduct three APU starts, since it is known that the battery performances are reduced at low temperatures. According to the tests carried out, the internal temperatures of the battery at the end of the flight sequence at -56°C are presented in the table 5-15.

Table 5-15 Internal temperatures of the batteries at the end of the flight sequence at -56°C

Flight sequence	Flight time	Li-Ion S1 Internal temperature	Li-Ion S2 Internal temperature	Ni-Cd Internal temperature
Short	96 min	Between -5°C and -20°C	Between -10°C and -20°C	Between 0°C and 10°C
Medium	210 min	-30°C	-34°C	-20°C
Long	618 min	-44°C	-40°C	-45°C

5.5 Flights with 80%+ SOC

Flights with a SOC of 80% and 90% are characterised as real because the TDS says “No take-off unless SOC is 80%” (rule in STD DO311). The table 5-16 shows the results of the tests with a SOC of 80% and more, regardless of test temperature.

Table 5-16 Flight results with 80%+ SOC

Battery	Number of tests at 80%+ SOC	Number of tests with failure	Success rate	Tests between -40°C and -20°C	Tests between 0°C and 70°C
Li-Ion S1	138	9	93.5%	4	134
Li-Ion S2	8	1	87.5%	1	7
Ni-Cd	12	1	91.7%	1	11

Li-Ion S1: For the 9 tests with failure, the test temperature was either 20°C or 30°C, however since for these tests the aircraft was staying only 20min on the ground, the battery internal temperature was at -25°C during the APU starts. The internal temperature is the factor limiting the battery performances in this case, therefore leading to a failure.

Li-Ion S2: Only 1 test at -20°C have been carried out and it failed. Cell overcharged is the cause of the failure, it happened after the three APU starts.

Ni-Cd: Only 1 test has failed to pass the three APU starts, the test conditions were 80% SOC and 0°C. However for this failed test, the internal temperature of the battery during the APU starts was -20°C. The negative temperature is the cause of the failure.

5.6 Statistics about the flight results

In the tables from 5-17 to 5-20, if there is an empty cell, this means no tests have been carried out at this temperature and SOC combination. At -40°C none of the tests succeeded to start the APU. At -20°C, the Li-Ion is able to conduct the APU starts with a lower SOC than the Ni-Cd. At 70°C, only the Ni-Cd battery succeeded to conduct three consecutive APU starts.

Table 5-17 Ni-Cd - Success rate of each SOC level according to the surrounding temperature

Ni-Cd: Success (%)		**Temperature (°C)**						
		-40	**-20**	**0**	**20**	**30**	**50**	**70**
SOC (%)	**40**	0	0				100	0
	70	0	0	100	100	100		100
	80			0			100	100
	90		100	100		100	100	

Table 5-18 Li-Ion S1 - Success rate of each SOC level according to the surrounding temperature

S1: Success (%)		**Temperature (°C)**						
		-40	**-20**	**0**	**20**	**30**	**50**	**70**
SOC (%)	**40**		28	100	80	70.8	0	
	70		100	100	100	100		
	80			100	80	80	100	
	90		100	100	100	100		

Table 5-19 Li-Ion S2 - Success rate of each SOC level according to the surrounding temperature

S2: Success (%)		**Temperature (°C)**									
		-40	**-35**	**-30**	**-25**	**-20**	**0**	**20**	**30**	**50**	**70**
SOC (%)	**40**	0				57.14				100	0
	70	0	100	100	100	80		100	100		
	80						100			100	0
	90					100	100		100	100	

Table 5-20 Li-Ion S2N - Success rate of each SOC level according to the surrounding temperature

S2N: Success (%)		**Temperature (°C)**						
		-40	**-20**	**0**	**20**	**30**	**50**	**70**
SOC (%)	**40**							
	70	0	57.14		100			
	80			100				
	90		100	100				

ATTENTION about the statistics results: Each SOC level has not been tested under the same conditions, thus, not the same amount of flights at the same temperatures.

5.7 Number of flight tested

The table 5-21 presents the number of flight tested for the Li-Ion and Ni-Cd batteries.

Table 5-21 Number of flight tested for each battery

Battery	**Executed flights**	**Successful**	**Failed**
Li-Ion S1	271	235	36
Li-Ion S2	35	21	14
Ni-Cd	32	16	16
Li-Ion S2N	15	8	7

5.8 Behaviour comparison

This section presents the behaviour differences between the S1, S2 and Ni-Cd batteries.

5.8.1 Recharging temperatures

Li-Ion S1: can be recharged at any temperature but its operating range is smaller than the one for the S2 and Ni-Cd batteries. The Operating range of the S1 battery is from -20°C to 30°C, however 1 test succeeded at 50°C. For more details about the operating range of each battery, see chapter *Statistics about the flights results* related to the S1 battery.
Li-Ion S2: during the tests at negative temperatures, the battery need to be warmed to 25°C before proceeding to the adjustment of the SOC. For the hot temperatures, the battery can be recharged at any temperature, e.g. at 50°C the SOC can be changed directly, there is no need to have the internal temperature of battery at 25°C.
Ni-Cd: for all the tests, before the SOC adjustment, the battery is heated or cooled until the internal temperature reaches 20°C or 30°C respectively.

5.8.2 SOC

Only the Li-Ion batteries have this technology, which displays in real time the remaining energy in the battery. At negative temperatures, for the S2 and S2N batteries, the algorithm computing the SOC is not working properly. The SOC is continuously changing. The battery is not being recharged or discharged while the SOC is increasing or decreasing at negative temperatures. The algorithm computing the SOC was working properly with the Li-Ion S1. The Ni-Cd does not have this technology.

5.8.3 Recharging current

When the battery is being recharged, the Li-Ion batteries use a current up to 60A and the Ni-Cd battery uses a current up to 27A.

CONCLUSION

During the flight simulations, the Li-Ion S1 has executed 271 tests, 235 were successful and 36 failed. As for the Li-Ion S2, 35 flights were performed, 14 of them failed. For the Ni-Cd battery, 32 flights were carried out, 16 of them failed.

According to the user manual, the Li-Ion batteries are designed to operate from -15°C to +71°C and the Ni-Cd from -40°C to +70°C. According to the tests carried out, the Li-Ion S1 is able to do an APU start from -20°C to 30°C at every SOC, furthermore one test has been carried out at 50°C with 80% SOC and it successfully passed the three APU starts. The Li-Ion S2 is able to do an APU start with an internal temperature of -35°C if the SOC is greater than or equal to 70%. The Li-Ion S2 operating range is from -35°C to 50°C. For the Ni-Cd the operating range is from -20°C to 70°C. All the batteries are not working at -40°C. With the Li-Ion S2, the system was able to perform the APU starts with an internal temperature of 69°C, however it was impossible to recharge the battery afterwards. For all the batteries, depending on the SOC the operating range may differ. In this paragraph, when a temperature range is mentioned, it does not mean the battery has a success rate of 100% to pass the test without a failure in this temperature range. It only shows where the battery is able to operate. See the statistics chapter to know the exact success rate for each temperature.

When just the flights with 80% and 90% SOC are taken into account, regardless of the temperature, the success rate is 93.5% for the Li-Ion S1, 87.5% for the Li-Ion S2 and 91.7% for Ni-Cd.

During the APU starts the Li-Ion voltage tends to stay closer to its nominal value compared to the Ni-Cd at same temperature. Therefore, the voltage drop from the nominal value is less important for the Li-Ion.

During the ground phase of 20 minutes between flights, the battery internal temperature will only increase by 6°C on average after a flight at -56°C. Therefore, the batteries can have difficulties to conduct three APU starts, since it is known that the battery performances are reduced at low temperatures.

At negative temperatures, the algorithm computing the SOC of the Li-Ion S2 and S2N is not working properly. The SOC is continuously changing. The battery is not being recharged or discharged while the SOC is increasing or decreasing at negative temperatures. The algorithm computing the SOC was working properly with the Li-Ion S1. The Ni-Cd does not have this technology.

The Li-Ion battery is 8kg lighter than the Ni-Cd battery, thanks to its higher energy density. However, the Li-Ion battery is equipped with a BMS which makes this battery bigger than the Ni-Cd battery.

Despite all the tests, the batteries did not show any signs of danger. Each time the Li-Ion batteries were tested outside of their limits, the BMS activated an alarm. The battery has multiple protection devices to exclude any risk of damage.

Before the Li-Ion will replace all the Ni-Cd batteries currently used by the aircraft industry, several non-technical factors will influence its deployment. The aircraft manufacturer decision to replace the Ni-Cd by the Li-Ion, will not only be influenced by the results of the tests carried out in this report. Factors such as the cost, life expectancy, and reliability; to name a few, will directly impact the choice of the technology to be used.

RECOMMENDATIONS

According to the test results, a recommendation for the Li-Ion and Ni-Cd batteries would be to add a heating device around the battery, thus the battery will never be too cold to start an APU. Since, after a flight at -56°C followed by a transition period of only 20min on the ground, the battery does not have the time to sufficiently heat up to start an APU.

Further research suggestions are an improvement of the SOC calculation system to be fully operational at temperatures below 0°C. The second one, is to test the batteries at different atmospheric pressures to check if the performances are still the same.

APPENDIX I

Ni-Cd

Electrical wiring and sensors

The image AI-1 shows the electrical wiring of the Ni-Cd bench test. The sensors also show where the measurements are taken.

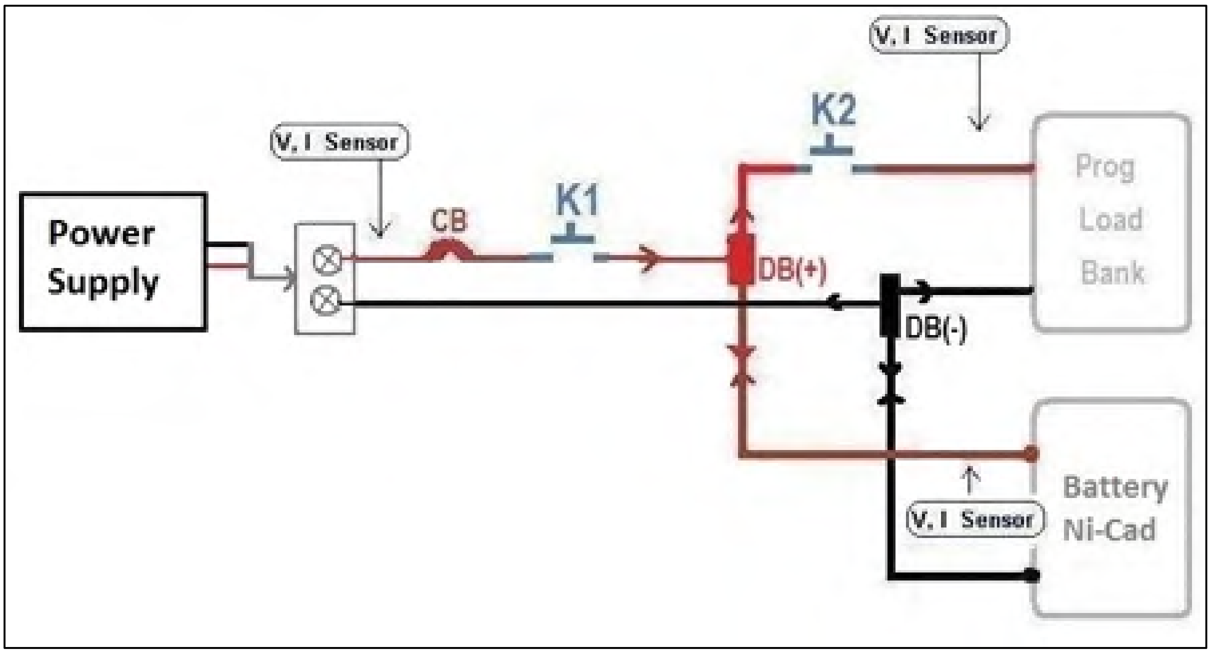

Figure-A I-1 Electrical wiring and sensors of the Ni-Cd bench test

Figure-A I-2 Ni-Cd battery photo

Testing software

Steps used in the LabVIEW program for the tests:

1. The battery is heated or cooled until the internal temperature reaches 20°C or 30°C respectively;
2. The battery is recharged until 100% SOC;
3. The battery is discharged to the desired SOC;
4. Cold soaking on the ground for 10 hours or 20minutes at the test temperature;
5. Power on the Aircraft (5 minutes);
6. APU 1 (20 seconds);
7. Delay (60 seconds);
8. APU 2 (20 seconds);
9. Delay (60 seconds);
10. APU 3 (20 seconds);
11. The battery is heated or cooled until the internal temperature reaches 20°C or 30°C respectively;
12. The battery is recharged until 100% SOC;
13. The battery is discharged to the desired SOC;
14. The temperature of the test chamber is updated to match the temperature of the previous cold soaking sequence for 20min;
15. Beginning of the flight.

SOC calculation method

The Ni-Cd does not have the electronics to display the SOC in real time. Therefore the SOC calculation method used is the following:

1. The battery is recharged until 100% SOC;
2. The battery is discharged during T minutes at 43A to obtain the desired SOC. Since it is known that the battery takes 1h with a 43A discharge current to go from 100% to 0% SOC.

Flights with APU start failure - comparison table

In the table AI-1, the current and voltage measurements were taken at the battery connectors. If a cell is filled with orange it means the value is below the minimum threshold.

Table-A I-1 Flights with APU start failure - comparison table (Ni-Cd)

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time	APU Max Current during APU (A)	APU Min Voltage during APU (V)
1	1	1	failed	40	-20	10h	792.846	4.315
6	1	6	failed	70	-40	10h	790.007	2.747
7	1	7	failed	70	-20	10h	804.686	11.612
9	1	9	failed	70	-40	10h	804.199	1.670
11	2	1	failed	40	-40	10h	425.847	0.203
14	2	4	failed	40	70	10h	751.892	8.713
15	2	5	failed	70	-20	10h	746.337	11.974
16	2	6	failed	40	-20	20min	746.134	0.155
17	2	7	failed	70	-40	10h	743.945	1.818
18	2	8	failed	80	0	20min	746.418	10.970
19	2	9	failed	70	-20	10h	746.499	9.537
23	3	1	failed	40	-20	10h	340.535	0.009
26	3	4	failed	70	-20	10h	747.594	9.539
27	3	5	failed	40	-20	20min	175.628	0.050
28	3	6	failed	40	-20	20min	91.289	0.044
29	3	7	failed	70	-40	10h	748.040	1.479

Flights results - comparison table

In the table AI-2, the current and voltage measurements were taken at the battery connectors. If a cell is filled with orange it means the value is below the minimum threshold.

Table-A I-2 Flight results - comparison table (Ni-Cd)

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time	APU Max Current during APU (A)	APU Min Voltage during APU (V)
1	1	1	failed	40	-20	10h	792.846	4.315
2	1	2	succeeded	70	30	10h	790.048	17.755
3	1	3	succeeded	80	50	10h	804.280	18.009
4	1	4	succeeded	90	0	10h	804.118	16.822
5	1	5	succeeded	40	50	10h	802.861	15.349
6	1	6	failed	70	-40	10h	790.007	2.747
7	1	7	failed	70	-20	10h	804.686	11.612
8	1	8	succeeded	90	30	10h	802.253	18.193
9	1	9	failed	70	-40	10h	804.199	1.670
10	1	10	succeeded	90	50	10h	802.699	18.019
11	2	1	failed	40	-40	10h	425.847	0.203
12	2	2	succeeded	70	20	10h	804.199	16.885
13	2	3	succeeded	80	70	10h	747.797	17.793
14	2	4	failed	40	70	10h	751.892	8.713
15	2	5	failed	70	-20	10h	746.337	11.974
16	2	6	failed	40	-20	20min	746.134	0.155
17	2	7	failed	70	-40	10h	743.945	1.818
18	2	8	failed	80	0	20min	746.418	10.970
19	2	9	failed	70	-20	10h	746.499	9.537
20	2	10	succeeded	90	50	10h	746.580	18.161
21	2	11	succeeded	70	70	10h	746.824	17.419
22	2	12	succeeded	90	50	20min	746.621	17.982
23	3	1	failed	40	-20	10h	340.535	0.009
24	3	2	succeeded	70	0	10h	747.351	15.151
25	3	3	succeeded	80	50	10h	756.028	17.852
26	3	4	failed	70	-20	10h	747.594	9.539
27	3	5	failed	40	-20	20min	175.628	0.050
28	3	6	failed	40	-20	20min	91.289	0.044

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time	APU Max Current during APU (A)	APU Min Voltage during APU (V)
29	3	7	failed	70	-40	10h	748.040	1.479
30	3	8	succeeded	90	50	10h	746.459	18.132
31	3	9	succeeded	80	50	10h	748.446	17.406
32	3	10	succeeded	90	-20	20min	747.270	17.090

Detailed statistics about the flights results

Table-A I-3 Ni-Cd detailed statistics about the flights results

Ni-Cd Battery		**Temperature (°C)**								
		-40			-20			0		
		Flight total	Success	%	Flight total	Success	%	Flight total	Success	%
SOC (%)	40	1	0	0.00	5	0	0.00	-	-	-
	70	4	0	0.00	4	0	0.00	1	1	100.00
	80	-	-	-	-	-	-	1	0	0.00
	90	-	-	-	1	1	100.00	1	1	100.00

Ni-Cd Battery		**Temperature (°C)**					
		20			30		
		Flight total	Success	%	Flight total	Success	%
SOC (%)	40	-	-	-	-	-	-
	70	1	1	100.00	1	1	100.00
	80	-	-	-	-	-	-
	90	-	-	-	1	1	100.00

Ni-Cd Battery		**Temperature (°C)**					
		50			70		
		Flight total	Success	%	Flight total	Success	%
SOC (%)	40	1	1	100.00	1	0	0.00
	70	-	-	-	1	1	100.00
	80	3	3	100.00	1	1	100.00
	90	4	4	100.00	-	-	-

APPENDIX II

Li-Ion

Electrical wiring and sensors

The image AII-1 shows the electrical wiring of the Li-Ion bench test. The sensors also show where the measurements are taken.

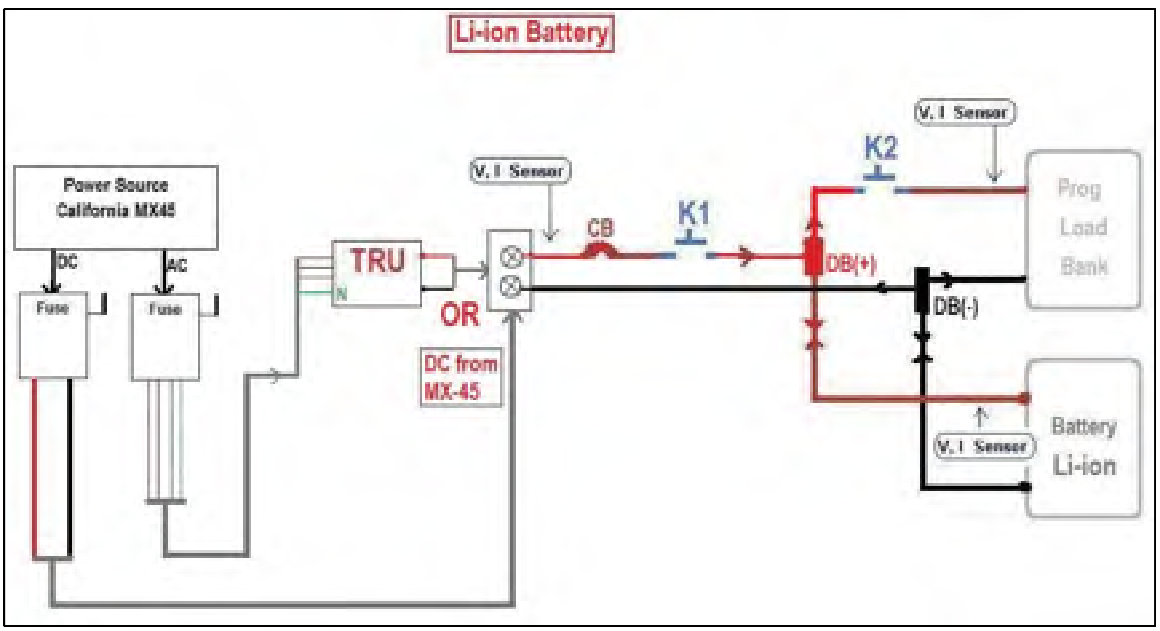

Figure-A II-1 Electrical wiring and sensors

Li-Ion battery detailed characteristics

Table-A II-1 Li-Ion battery detailed characteristics (Source: User manual)

Definition	Values
Nominal Capacity (Ah)	45
Nominal Voltage (V)	25
Energy (Wh)	1125
Operating Temperature (°C).	-15 / +71
Weight (Kg) – (LBS)	30.2 - 66
Height (mm)	336
Width (mm)	350
Length (mm)	339
Cells	2 rows of 7 cells VL30P (14 Li-Ion cells), connected in parallel. The 7 cells of each row are connected with each other in series.
Cells characteristics	VL30P cell operates between 4000mV and 3300mV
Venting Hole - Max gas flow (L/sec)	157

Figure-A II-2 Li-Ion battery photo

Flights with test failure

Table-A II-2 S1 Battery - Flights with test failure

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time
1	1	1	failed	40%	-20	10h
11	1	11	failed	80%	20	20min
31	2	7	failed	80%	30	20min
33	2	9	failed	40%	-20	20min
39	2	15	failed	80%	20	20min
49	3	1	failed	40%	-20	10h
55	3	7	failed	80%	20	20min
57	3	9	failed	40%	-20	20min
65	3	17	failed	40%	30	20min
73	1.2	1	failed	40%	-20	10h
81	1.2	9	failed	40%	20	20min
103	2.2	7	failed	80%	30	20min
105	2.2	9	failed	40%	-20	20min
111	2.2	15	failed	80%	20	20min
121	3.2	1	failed	40%	-20	10h
127	3.2	7	failed	80%	20	20min
129	3.2	9	failed	40%	-20	20min
137	3.2	17	failed	40%	30	20min
145	1.3	1	failed	40%	-20	10h
175	2.3	7	failed	80%	30	20min
177	2.3	9	failed	40%	-20	20min
183	2.3	15	failed	80%	20	20min
193	3.3	1	failed	40%	-20	10h
201	3.3	9	failed	40%	-20	1h
209	3.3	17	failed	40%	30	1h
249	2.4	9	failed	40%	-20	1h
257	2.4	17	failed	40%	30	20min
265	3.4	1	failed	40%	-20	10h
273	3.4	9	failed	40%	-20	1h30
281	3.4	17	failed	40%	30	20min
321	2.5	9	failed	40%	-20	1h30
329	2.5	17	failed	40%	30	20min
337	3.5	1	failed	40%	-20	10h
345	3.5	9	failed	40%	-20	1h30
353	3.5	17	failed	40%	30	1h

Table-A II-3 S2 Battery - Flights with test failure

Flight total	**Cycle**	**Flight**	**Result**	**SOC to Test (%)**	**Temp (°C)**	**Ground time**
			Cold			
1	1	1	failed	40	-20	10h
2	1	6	failed	70	-40	10h
4	1	14	failed	70	-40	10h
5	2	1	failed	40	-40	10h
6	2	6	failed	70	-20	10h
8	2	10	failed	70	-40	10h
10	3	1	failed	40	-20	10h
14	3	14	failed	70	-40	10h
16	1	1	failed	40	-20	10h
17	1	6	failed	70	-40	10h
19	1	14	failed	70	-40	10h
22	2	10	failed	70	-40	10h
			Hot			
8	2	3	failed	80	70	10h
9	2	5	failed	40	70	10h

Table-A II-4 S2N Battery - Flights with test failure

Flight tot	**Cycle**	**Flight**	**Result**	**SOC to Test (%)**	**Temp (°C)**	**Ground time**
3	1	3	failed	70	-40	10h
4	1	4	failed	70	-20	10h
5	1	5	failed	70	-40	10h
8	2	3	failed	70	-20	10h
9	2	4	failed	70	-20	20min
10	2	5	failed	70	-40	10h
17	3	5	failed	70	-40	10h

Flight results

Table-A II-5 S1 Battery - Flights results

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time
Round 1						
1	1	1	failed	40%	-20	10h
2	1	2	succeeded	70%	30	10h
3	1	3	succeeded	80%	50	10h
4	1	4	succeeded	90%	0	10h
5	1	5	succeeded	40%	50	10h
6	1	6	not executed	70%	-40	10h
7	1	7	succeeded	80%	20	20min
8	1	8	succeeded	90%	30	10h
9	1	9	succeeded	40%	20	20min
10	1	10	succeeded	70%	-20	10h
11	1	11	failed	80%	20	20min
12	1	12	succeeded	90%	30	10h
13	1	13	succeeded	40%	0	20min
14	1	14	not executed	70%	-40	10h
15	1	15	succeeded	80%	20	20min
16	1	16	not executed	90%	50	10h
17	1	17	succeeded	40%	30	20min
18	1	18	succeeded	70%	20	10h
19	1	19	succeeded	80%	0	10h
20	1	20	succeeded	90%	20	20min
21	1	21	not executed	40%	50	10h
22	1	22	succeeded	70%	20	20min
23	1	23	succeeded	80%	0	10h
24	1	24	succeeded	90%	30	20min
25	2	1	not executed	40%	-40	10h
26	2	2	succeeded	70%	20	10h
27	2	3	not executed	80%	70	10h
28	2	4	succeeded	90%	20	10h
29	2	5	not executed	40%	70	10h
30	2	6	succeeded	70%	-20	10h
31	2	7	failed	80%	30	20min
32	2	8	succeeded	90%	20	10h
33	2	9	failed	40%	-20	20min

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time
34	2	10	not executed	70%	-40	10h
35	2	11	succeeded	80%	0	20min
36	2	12	succeeded	90%	20	10h
37	2	13	succeeded	40%	0	20min
38	2	14	succeeded	70%	-20	10h
39	2	15	failed	80%	20	20min
40	2	16	not executed	90%	50	10h
41	2	17	succeeded	40%	30	20min
42	2	18	not executed	70%	70	10h
43	2	19	succeeded	80%	30	10h
44	2	20	succeeded	90%	20	20min
45	2	21	succeeded	40%	0	10h
46	2	22	succeeded	70%	20	20min
47	2	23	succeeded	80%	30	10h
48	2	24	not executed	90%	50	20min
49	3	1	failed	40%	-20	10h
50	3	2	succeeded	70%	0	10h
51	3	3	not executed	80%	50	10h
52	3	4	succeeded	90%	20	10h
53	3	5	succeeded	40%	30	10h
54	3	6	succeeded	70%	-20	10h
55	3	7	failed	80%	20	20min
56	3	8	succeeded	90%	30	10h
57	3	9	failed	40%	-20	20min
58	3	10	succeeded	70%	0	10h
59	3	11	succeeded	80%	20	20min
60	3	12	succeeded	90%	30	10h
61	3	13	succeeded	40%	-20	20min
62	3	14	not executed	70%	-40	10h
63	3	15	succeeded	80%	0	20min
64	3	16	not executed	90%	50	10h
65	3	17	failed	40%	30	20min
66	3	18	succeeded	70%	20	10h
67	3	19	not executed	80%	50	10h
68	3	20	succeeded	90%	-20	20min
69	3	21	succeeded	40%	30	10h
70	3	22	succeeded	70%	20	20min
71	3	23	succeeded	80%	0	10h

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time
72	3	24	succeeded	90%	20	20min
Round 2						
73	1.2	1	failed	40%	-20	10h
74	1.2	2	succeeded	70%	30	10h
75	1.2	3	not executed	80%	50	10h
76	1.2	4	succeeded	90%	0	10h
77	1.2	5	not executed	40%	50	10h
78	1.2	6	not executed	70%	-40	10h
79	1.2	7	succeeded	80%	20	20min
80	1.2	8	succeeded	90%	30	10h
81	1.2	9	failed	40%	20	20min
82	1.2	10	succeeded	70%	-20	10h
83	1.2	11	succeeded	80%	20	1h30
84	1.2	12	succeeded	90%	30	10h
85	1.2	13	succeeded	40%	0	20min
86	1.2	14	not executed	70%	-40	10h
87	1.2	15	succeeded	80%	20	20min
88	1.2	16	not executed	90%	50	10h
89	1.2	17	succeeded	40%	30	20min
90	1.2	18	succeeded	70%	20	10h
91	1.2	19	succeeded	80%	0	10h
92	1.2	20	succeeded	90%	20	20min
93	1.2	21	not executed	40%	50	10h
94	1.2	22	succeeded	70%	20	20min
95	1.2	23	succeeded	80%	0	10h
96	1.2	24	succeeded	90%	30	20min
97	2.2	1	not executed	40%	-40	10h
98	2.2	2	succeeded	70%	20	10h
99	2.2	3	not executed	80%	70	10h
100	2.2	4	succeeded	90%	20	10h
101	2.2	5	not executed	40%	70	10h
102	2.2	6	succeeded	70%	-20	10h
103	2.2	7	failed	80%	30	20min
104	2.2	8	succeeded	90%	20	10h
105	2.2	9	failed	40%	-20	20min
106	2.2	10	not executed	70%	-40	10h
107	2.2	11	succeeded	80%	0	20min

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time
108	2.2	12	succeeded	90%	20	10h
109	2.2	13	succeeded	40%	0	20min
110	2.2	14	succeeded	70%	-20	10h
111	2.2	15	failed	80%	20	20min
112	2.2	16	not executed	90%	50	10h
113	2.2	17	succeeded	40%	30	20min
114	2.2	18	not executed	70%	70	10h
115	2.2	19	succeeded	80%	30	10h
116	2.2	20	succeeded	90%	20	20min
117	2.2	21	succeeded	40%	0	10h
118	2.2	22	succeeded	70%	20	20min
119	2.2	23	succeeded	80%	30	10h
120	2.2	24	not executed	90%	50	20min
121	3.2	1	failed	40%	-20	10h
122	3.2	2	succeeded	70%	0	10h
123	3.2	3	not executed	80%	50	10h
124	3.2	4	succeeded	90%	20	10h
125	3.2	5	succeeded	40%	30	10h
126	3.2	6	succeeded	70%	-20	10h
127	3.2	7	failed	80%	20	20min
128	3.2	8	succeeded	90%	30	10h
129	3.2	9	failed	40%	-20	20min
130	3.2	10	succeeded	70%	0	10h
131	3.2	11	succeeded	80%	20	20min
132	3.2	12	succeeded	90%	30	10h
133	3.2	13	succeeded	40%	-20	20min
134	3.2	14	not executed	70%	-40	10h
135	3.2	15	succeeded	80%	0	20min
136	3.2	16	not executed	90%	50	10h
137	3.2	17	failed	40%	30	20min
138	3.2	18	succeeded	70%	20	10h
139	3.2	19	not executed	80%	50	10h
140	3.2	20	succeeded	90%	-20	20min
141	3.2	21	succeeded	40%	30	10h
142	3.2	22	succeeded	70%	20	20min
143	3.2	23	succeeded	80%	0	10h
144	3.2	24	succeeded	90%	20	20min

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time
Round 3						
145	1.3	1	failed	40%	-20	10h
146	1.3	2	succeeded	70%	30	10h
147	1.3	3	not executed	80%	50	10h
148	1.3	4	succeeded	90%	0	10h
149	1.3	5	not executed	40%	50	10h
150	1.3	6	not executed	70%	-40	10h
151	1.3	7	succeeded	80%	20	20min
152	1.3	8	succeeded	90%	30	10h
153	1.3	9	succeeded	40%	20	20min
154	1.3	10	succeeded	70%	-20	10h
155	1.3	11	succeeded	80%	20	1h30
156	1.3	12	succeeded	90%	30	10h
157	1.3	13	succeeded	40%	0	20min
158	1.3	14	not executed	70%	-40	10h
159	1.3	15	succeeded	80%	20	20min
160	1.3	16	not executed	90%	50	10h
161	1.3	17	succeeded	40%	30	20min
162	1.3	18	succeeded	70%	20	10h
163	1.3	19	succeeded	80%	0	10h
164	1.3	20	succeeded	90%	20	20min
165	1.3	21	not executed	40%	50	10h
166	1.3	22	succeeded	70%	20	20min
167	1.3	23	succeeded	80%	0	10h
168	1.3	24	succeeded	90%	30	20min
169	2.3	1	not executed	40%	-40	10h
170	2.3	2	succeeded	70%	20	10h
171	2.3	3	not executed	80%	70	10h
172	2.3	4	succeeded	90%	20	10h
173	2.3	5	not executed	40%	70	10h
174	2.3	6	succeeded	70%	-20	10h
175	2.3	7	failed	80%	30	20min
176	2.3	8	succeeded	90%	20	10h
177	2.3	9	failed	40%	-20	20min
178	2.3	10	not executed	70%	-40	10h
179	2.3	11	succeeded	80%	0	20min
180	2.3	12	succeeded	90%	20	10h
181	2.3	13	succeeded	40%	0	20min

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time
182	2.3	14	succeeded	70%	-20	10h
183	2.3	15	failed	80%	20	20min
184	2.3	16	not executed	90%	50	10h
185	2.3	17	succeeded	40%	30	20min
186	2.3	18	not executed	70%	70	10h
187	2.3	19	succeeded	80%	30	10h
188	2.3	20	succeeded	90%	20	20min
189	2.3	21	succeeded	40%	0	10h
190	2.3	22	succeeded	70%	20	20min
191	2.3	23	succeeded	80%	30	10h
192	2.3	24	not executed	90%	50	20min
193	3.3	1	failed	40%	-20	10h
194	3.3	2	succeeded	70%	0	10h
195	3.3	3	not executed	80%	50	10h
196	3.3	4	succeeded	90%	20	10h
197	3.3	5	succeeded	40%	30	10h
198	3.3	6	succeeded	70%	-20	10h
199	3.3	7	succeeded	80%	20	1h
200	3.3	8	succeeded	90%	30	10h
201	3.3	9	failed	40%	-20	1h
202	3.3	10	succeeded	70%	0	10h
203	3.3	11	succeeded	80%	20	20min
204	3.3	12	succeeded	90%	30	10h
205	3.3	13	succeeded	40%	-20	20min
206	3.3	14	not executed	70%	-40	10h
207	3.3	15	succeeded	80%	0	20min
208	3.3	16	not executed	90%	50	10h
209	3.3	17	failed	40%	30	1h
210	3.3	18	succeeded	70%	20	10h
211	3.3	19	not executed	80%	50	10h
212	3.3	20	succeeded	90%	-20	20min
213	3.3	21	succeeded	40%	30	10h
214	3.3	22	succeeded	70%	20	20min
215	3.3	23	succeeded	80%	0	10h
216	3.3	24	succeeded	90%	20	20min
Round 4						
217	1.4	1	succeeded	40%	-20	10h
218	1.4	2	succeeded	70%	30	10h

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time
219	1.4	3	not executed	80%	50	10h
220	1.4	4	succeeded	90%	0	10h
221	1.4	5	not executed	40%	50	10h
222	1.4	6	not executed	70%	-40	10h
223	1.4	7	succeeded	80%	20	20min
224	1.4	8	succeeded	90%	30	10h
225	1.4	9	succeeded	40%	20	20min
226	1.4	10	succeeded	70%	-20	10h
227	1.4	11	succeeded	80%	20	1h
228	1.4	12	succeeded	90%	30	10h
229	1.4	13	succeeded	40%	0	20min
230	1.4	14	not executed	70%	-40	10h
231	1.4	15	succeeded	80%	20	20min
232	1.4	16	not executed	90%	50	10h
233	1.4	17	succeeded	40%	30	20min
234	1.4	18	succeeded	70%	20	10h
235	1.4	19	succeeded	80%	0	10h
236	1.4	20	succeeded	90%	20	20min
237	1.4	21	not executed	40%	50	10h
238	1.4	22	succeeded	70%	20	20min
239	1.4	23	succeeded	80%	0	10h
240	1.4	24	succeeded	90%	30	20min
241	2.4	1	not executed	40%	-40	10h
242	2.4	2	succeeded	70%	20	10h
243	2.4	3	not executed	80%	70	10h
244	2.4	4	succeeded	90%	20	10h
245	2.4	5	not executed	40%	70	10h
246	2.4	6	succeeded	70%	-20	10h
247	2.4	7	succeeded	80%	30	1h
248	2.4	8	succeeded	90%	20	10h
249	2.4	9	failed	40%	-20	1h
250	2.4	10	not executed	70%	-40	10h
251	2.4	11	succeeded	80%	0	20min
252	2.4	12	succeeded	90%	20	10h
253	2.4	13	succeeded	40%	0	20min
254	2.4	14	succeeded	70%	-20	10h
255	2.4	15	succeeded	80%	20	20min
256	2.4	16	not executed	90%	50	10h

Flight total	**Cycle**	**Flight**	**Result**	**SOC to Test (%)**	**Temp (°C)**	**Ground time**
257	2.4	17	failed	40%	30	20min
258	2.4	18	not executed	70%	70	10h
259	2.4	19	succeeded	80%	30	10h
260	2.4	20	succeeded	90%	20	20min
261	2.4	21	succeeded	40%	0	10h
262	2.4	22	succeeded	70%	20	20min
263	2.4	23	succeeded	80%	30	10h
264	2.4	24	not executed	90%	50	20min
265	3.4	1	failed	40%	-20	10h
266	3.4	2	succeeded	70%	0	10h
267	3.4	3	not executed	80%	50	10h
268	3.4	4	succeeded	90%	20	10h
269	3.4	5	succeeded	40%	30	10h
270	3.4	6	succeeded	70%	-20	10h
271	3.4	7	succeeded	80%	20	1h
272	3.4	8	succeeded	90%	30	10h
273	3.4	9	failed	40%	-20	1h30
274	3.4	10	succeeded	70%	0	10h
275	3.4	11	succeeded	80%	20	20min
276	3.4	12	succeeded	90%	30	10h
277	3.4	13	succeeded	40%	-20	20min
278	3.4	14	not executed	70%	-40	10h
279	3.4	15	succeeded	80%	0	20min
280	3.4	16	not executed	90%	50	10h
281	3.4	17	failed	40%	30	20min
282	3.4	18	succeeded	70%	20	10h
283	3.4	19	not executed	80%	50	10h
284	3.4	20	succeeded	90%	-20	20min
285	3.4	21	succeeded	40%	30	10h
286	3.4	22	succeeded	70%	20	20min
287	3.4	23	succeeded	80%	0	10h
288	3.4	24	succeeded	90%	20	20min
Round 5						
289	1.5	1	succeeded	40%	-20	10h
290	1.5	2	succeeded	70%	30	10h
291	1.5	3	not executed	80%	50	10h
292	1.5	4	succeeded	90%	0	10h
293	1.5	5	not executed	40%	50	10h

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time
294	1.5	6	not executed	70%	-40	10h
295	1.5	7	succeeded	80%	20	20min
296	1.5	8	succeeded	90%	30	10h
297	1.5	9	succeeded	40%	20	20min
298	1.5	10	succeeded	70%	-20	10h
299	1.5	11	succeeded	80%	20	1h
300	1.5	12	succeeded	90%	30	10h
301	1.5	13	succeeded	40%	0	20min
302	1.5	14	not executed	70%	-40	10h
303	1.5	15	succeeded	80%	20	20min
304	1.5	16	not executed	90%	50	10h
305	1.5	17	succeeded	40%	30	20min
306	1.5	18	succeeded	70%	20	10h
307	1.5	19	succeeded	80%	0	10h
308	1.5	20	succeeded	90%	20	20min
309	1.5	21	not executed	40%	50	10h
310	1.5	22	succeeded	70%	20	20min
311	1.5	23	succeeded	80%	0	10h
312	1.5	24	succeeded	90%	30	20min
313	2.5	1	not executed	40%	-40	10h
314	2.5	2	succeeded	70%	20	10h
315	2.5	3	not executed	80%	70	10h
316	2.5	4	succeeded	90%	20	10h
317	2.5	5	not executed	40%	70	10h
318	2.5	6	succeeded	70%	-20	10h
319	2.5	7	succeeded	80%	30	1h
320	2.5	8	succeeded	90%	20	10h
321	2.5	9	failed	40%	-20	1h30
322	2.5	10	not executed	70%	-40	10h
323	2.5	11	succeeded	80%	0	20min
324	2.5	12	succeeded	90%	20	10h
325	2.5	13	succeeded	40%	0	20min
326	2.5	14	succeeded	70%	-20	10h
327	2.5	15	succeeded	80%	20	1h
328	2.5	16	not executed	90%	50	10h
329	2.5	17	failed	40%	30	20min
330	2.5	18	not executed	70%	70	10h
331	2.5	19	succeeded	80%	30	10h

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time
332	2.5	20	succeeded	90%	20	20min
333	2.5	21	succeeded	40%	0	10h
334	2.5	22	succeeded	70%	20	20min
335	2.5	23	succeeded	80%	30	10h
336	2.5	24	not executed	90%	50	20min
337	3.5	1	failed	40%	-20	10h
338	3.5	2	succeeded	70%	0	10h
339	3.5	3	not executed	80%	50	10h
340	3.5	4	succeeded	90%	20	10h
341	3.5	5	succeeded	40%	30	10h
342	3.5	6	succeeded	70%	-20	10h
343	3.5	7	succeeded	80%	20	20min
344	3.5	8	succeeded	90%	30	10h
345	3.5	9	failed	40%	-20	1h30
346	3.5	10	succeeded	70%	0	10h
347	3.5	11	succeeded	80%	20	20min
348	3.5	12	succeeded	90%	30	10h
349	3.5	13	succeeded	40%	-20	20min
350	3.5	14	not executed	70%	-40	10h
351	3.5	15	succeeded	80%	0	20min
352	3.5	16	not executed	90%	50	10h
353	3.5	17	failed	40%	30	1h
354	3.5	18	not executed	70%	20	10h
355	3.5	19	not executed	80%	50	10h
356	3.5	20	not executed	90%	-20	20min
357	3.5	21	not executed	40%	30	10h
358	3.5	22	not executed	70%	20	20min
359	3.5	23	not executed	80%	0	10h
360	3.5	24	not executed	90%	20	20min

Table-A II-6 S2 Battery - Flights results

Flight total	**Cycle**	**Flight**	**Result**	**SOC to Test (%)**	**Temp (°C)**	**Ground time**
			Hot			
1	1	2	succeeded	70	30	10h
2	1	3	succeeded	80	50	10h
3	1	4	succeeded	90	0	10h
4	1	5	succeeded	40	50	10h
5	1	12	succeeded	90	30	10h
6	1	16	succeeded	90	50	10h
7	2	2	succeeded	70	20	10h
8	2	3	failed	80	70	10h
9	2	5	failed	40	70	10h
10	2	11	succeeded	80	0	10h
11	2	16	succeeded	90	50	10h
			Cold			
1	1	1	failed	40	-20	10h
2	1	6	failed	70	-40	10h
3	1	10	succeeded	70	-20	10h
4	1	14	failed	70	-40	10h
5	2	1	failed	40	-40	10h
6	2	6	failed	70	-20	10h
7	2	9	succeeded	40	-20	20min
8	2	10	failed	70	-40	10h
9	2	14	succeeded	70	-20	10h
10	3	1	failed	40	-20	10h
11	3	6	succeeded	70	-20	10h
12	3	9	succeeded	40	-20	20min
13	3	13	succeeded	40	-20	20min
14	3	14	failed	70	-40	10h
15	3	20	succeeded	90	-20	20min
16	1	1	failed	40	-20	10h
17	1	6	failed	70	-40	10h
18	1	10	succeeded	70	-20	10h
19	1	14	failed	70	-40	10h
20	Test: -25°C		succeeded	70	-25	10h
21	2	9	succeeded	40	-20	20min
22	2	10	failed	70	-40	10h
23	Test: -30°C		succeeded	70	-30	10h
24	Test: -35°C		succeeded	70	-35	10h

Table-A II-7 S2N Battery - Flights results

Flight total	Cycle	Flight	Result	SOC to Test (%)	Temp (°C)	Ground time
1	1	1	succeeded	70	-20	10h
2	1	2	succeeded	90	0	10h
3	1	3	failed	70	-40	10h
4	1	4	failed	70	-20	10h
5	1	5	failed	70	-40	10h
6	2	1	not executed	-	-	10h
7	2	2	succeeded	70	20	10h
8	2	3	failed	70	-20	10h
9	2	4	failed	70	-20	20min
10	2	5	failed	70	-40	10h
11	2	6	succeeded	80	0	20min
12	2	7	succeeded	70	-20	10h
13	3	1	not executed	-	-	10h
14	3	2	not executed	-	-	10h
15	3	3	succeeded	70	-20	20min
16	3	4	succeeded	70	-20	20min
17	3	5	failed	70	-40	10h
18	3	6	succeeded	90	-20	20min

Detailed statistics about the flights results

Table-A II-8 S1 detailed statistics about the flights results

S1 Battery		**Temperature (°C)**								
		-40			-20			0		
		Flight tot	Success	%	Flight tot	Success	%	Flight tot	Success	%
SOC (%)	40	-	-	-	25	7	28.00	15	15	100.00
	70	-	-	-	20	20	100.00	10	10	100.00
	80	-	-	-	-	-	-	24	24	100.00
	90	-	-	-	4	4	100.00	5	5	100.00

S1 Battery		**Temperature (°C)**					
		20			30		
		Flight tot	Success	%	Flight tot	Success	%
SOC (%)	40	5	4	80.00	24	17	70.83
	70	28	28	100.00	5	5	100.00
	80	30	24	80.00	15	12	80.00
	90	34	34	100.00	25	25	100.00

S1 Battery		**Temperature (°C)**					
		50			70		
		Flight tot	Success	%	Flight tot	Success	%
SOC (%)	40	1	0	0.00	-	-	-
	70	-	-	-	-	-	-
	80	1	1	100.00	-	-	-
	90	-	-	-	-	-	-

Table-A II-9 S2 detailed statistics about the flights results

S2 Battery		Temperature (°C)								
		-40			-35			-30		
		Flight tot	Success	%	Flight tot	Success	%	Flight tot	Success	%
SOC (%)	40	1	0	0.00	-	-	-	-	-	-
	70	7	0	0.00	1	1	100.00	1	1	100.00
	80	-	-	-	-	-	-	-	-	-
	90	-	-	-	-	-	-	-	-	-

S2 Battery		Temperature (°C)								
		-25			-20			0		
		Flight tot	Success	%	Flight tot	Success	%	Flight tot	Success	%
SOC (%)	40	-	-	-	7	4	57.14	-	-	-
	70	1	1	100.00	5	4	80.00	-	-	-
	80	-	-	-	-	-	-	1	1	100.00
	90	-	-	-	1	1	100.00	1	1	100.00

S2 Battery		Temperature (°C)					
		20			30		
		Flight tot	Success	%	Flight tot	Success	%
SOC (%)	40	-	-	-	-	-	-
	70	1	1	100.00	1	1	100.00
	80	-	-	-	-	-	-
	90	-	-	-	1	1	100.00

S2 Battery		Temperature (°C)					
		50			70		
		Flight tot	Success	%	Flight tot	Success	%
SOC (%)	40	1	1	100.00	1	0	0.00
	70	-	-	-	-	-	-
	80	1	1	100.00	1	0	0.00
	90	2	2	100.00	-	-	-

Table-A II-10 S2N detailed statistics about the flights results

S2N Battery		**Temperature (°C)**					
		-40			-20		
		Flight tot	Success	%	Flight tot	Success	%
SOC (%)	40	-	-	-	-	-	-
	70	4	0	0.00	7	4	57.14
	80	-	-	-	-	-	-
	90	-	-	-	1	1	100.00

S2N Battery		**Temperature (°C)**					
		0			20		
		Flight tot	Success	%	Flight tot	Success	%
SOC (%)	40	-	-	-	-	-	-
	70	-	-	-	1	1	100.00
	80	1	1	100.00	-	-	-
	90	1	1	100.00	-	-	-

S2N Battery		**Temperature (°C)**								
		30			50			70		
		Flight tot	Success	%	Flight tot	Success	%	Flight tot	Success	%
SOC (%)	40	-	-	-	-	-	-	-	-	-
	70	-	-	-	-	-	-	-	-	-
	80	-	-	-	-	-	-	-	-	-
	90	-	-	-	-	-	-	-	-	-

Testing software

Battery S1

Steps used in the LabVIEW program for the tests:

1. Battery is recharged to the desired SOC, the temperature of the test is fixed, cold soaking on ground for 10 hours or 20 minutes;
2. Power on the Aircraft (5 minutes);
3. APU 1 (20 seconds);
4. Delay (60 seconds);
5. APU 2 (20 seconds);
6. Delay (60 seconds);
7. APU 3 (20 seconds);
8. Battery is recharged to 80% at the test temperature;
9. Beginning of the flight.

Battery S2

Steps used in LabVIEW program for the tests:

1. The battery is heated over 20°C;
2. Battery is recharged to the desired SOC;
3. Wait 30min;
4. The temperature of the test is fixed, cold soaking on ground for 10 hours or 20minutes;
5. Power on the Aircraft;
6. APU 1 (20 seconds);
7. Delay (60 seconds);
8. APU 2 (20 seconds);
9. Delay (60 seconds);
10. APU 3 (20 seconds);
11. Wait 30min;
12. The temperature of the test chamber is fixed at 25°C, the battery is recharged to100%;

13. The battery is discharged to 80%;
14. The temperature of the test chamber is updated to match the temperature of the previous cold soaking;
15. Beginning of the flight.

Battery S2N

The steps in the LabVIEW program were the same as these used for the battery S2; however, the APU profile has changed and runs for 60 seconds. The Flight 4 of the cycle 1 and the Flights 3 and 4 of the cycle 2 (Battery at -20°C and 70% SOC) failed after the completion of the three APU starts. The scenarios were again simulated in the flight 7 of the cycle 2 and the flights 3, 4 and 6 of the cycle 3 with the waiting time of 30 min (step 12) deleted from the program. The flights succeeded this time.

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