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Performance Evaluation of Lithium-ion Batteries under Low-Pressure Conditions for Aviation Applications

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Abstract

Electrification is getting more important in the aviation industry with the increasing need for reducing emissions of carbon dioxide and fuel consumption. It is crucial to assess the behavior of Li-Ion batteries at high-altitude conditions to design safe and reliable battery packs. This paper aims at benchmarking the performance of different formats of battery cells (pouch cells and cylindrical cells) in low-pressure environments. A test setup was designed and fabricated to replicate the standard procedure defined by the RTCA DO-311 standard, such as the altitude test and rapid decompression test. During the test voltage, current, temperature, and pressure were monitored, and the evaluation criteria is based on the capacity retention, along with the structural integrity of the cell. From preliminary tests, it was observed that cylindrical cells do not show a significant change in performance at low-pressure conditions thanks to their steel casing. Failure has been observed in pouch cells due to the absence of a rigid enclosure.

Introduction

Volatile oil prices, increasing air travel demand, emissions impact on climate, and limited performance of existing aircraft technologies have generated substantial interest in hybrid electric aviation and urban air mobility [1]. Many of the proposed architectures of electrified aircraft include the integration of lithium-ion batteries (LIB). The use of LIBs for aviation introduces new safety and technical concerns, especially considering the different environmental conditions (ambient pressure, temperature) [2]. The failure mechanisms of LIBs may be attributed to the system, such as issues with the cooling systems or the terminal actuator, or they may result from the failure of the voltage, current, or temperature sensors, or they may result from the battery cell itself, such as internal short circuits, electrolyte leakage, degradation, or thermal runaway [3,4]. All these potential issues are interconnected and can cause the cell to operate outside of the manufacturer's specifications, resulting in accelerated degradation, battery swelling, mechanical damage, and, eventually, thermal runaway [3,4]. To address these issues, optimal sensor placement and fault diagnosis techniques can be used at the system level [3,4,5], although cell selection is critical to ensure safety, and prevent catastrophic events. While there are special batteries developed for aerospace applications, the aviation, and air mobility industry require the availability of low-cost commercial LIB capable of withstanding specific environmental pressure and temperature conditions [6]. The main hazards for aircraft electrification come from the risk of thermal runaway and energy uncertainty of the battery pack [7]. Reliable operation of LIB for aviation needs to be verified at the proper environmental conditions, at low pressure is fundamental to be able to assess the capability of a battery cell to withstand flight conditions, flight anomalies, and the ability to be compliant with standard requirements, such as Radio Technical Commission for Aeronautics (RTCA) DO-311. LIBs at low-pressure conditions have shown the risk of swelling and electrolyte leakage caused by the pressure difference between the environment and the inside of the battery, generating flammable gasses with the risk of thermal runaway and flame propagation with the adjacent cells [8].

Previous literature attempts to characterize cylindrical cells [9], and pouch cells [10,11,12] under low-pressure conditions for small satellite applications using vacuum chambers. Cook et al. and Clark et al. [9,11] attempt to characterize cells for CubeSats application. Cell testing was conducted in Low Earth Orbit (LEO) conditions to assess the performance and cycle life. Cook et al. [9] after testing several cylindrical cells in a vacuum chamber placed inside an environmental chamber, without including any system to control the skin temperature of the cell, suggest characterizing the cell for the specific mission profile because testing did not provide useful information for CubeSat applications. Jeevarajan et al. [10] show that pouch cells restrained in Lexan plates with a pressure applied compatibly with the manufacturer specifications can better withstand space application compared to unrestrained cells. In order to minimize deterioration, the author suggests operating pouch cells at an environmental pressure of 8-10 psi (55-69 kPa). Clark et al. [11] tested pouch cells for CubeSats without a restraining device, utilizing a cold plate cooled via a water loop for temperature control, however the cell swelled during the test in vacuum, decreasing surface contact with the cold plate, causing a temperature rise during the test. Ooto, Hiroki, et al [12] attempted to overcome the problem of pouch cell swelling by substituting the polymer pouch bag with a stainless-steel pouch, which improved the performance of the cell tested in a low-pressure environment and prevented cell swelling. The aforementioned publications offer a helpful understanding of how low pressure affects LIBs, however, there is significant potential to advance the state of the art in the field, especially with the consideration of different battery chemistries, varying vehicle architectures, and new applications such as advanced air mobility. Additionally, there is a lack of literature on how standards and regulations are utilized to evaluate LIBs for low-pressure conditions experienced in electrified aviation applications.

This paper aims at assessing the performance and standard compliance of LIB under low-pressure conditions starting from available testing standards. Multiple standards for performance and safety assessment of LIB are available from organizations such as SAE, UN, IEC, and UL and are tailored for applications ranging from consumer electronics to automotive and stationary storage. While these standards provide requirements and testing procedures considering electrical, thermal, environmental, and mechanical factors, there isn't a lot of focus on low-pressure conditions. As part of these general LIB standards, the only test that considers low pressure is the Altitude Test defined as part of the UN 38.3 standard for the transportation of LIB. The UN38.3 Altitude test only considers storage under low-pressure conditions as part of air transportation and does not provide any guidance on the performance requirements for LIB cycled under low-pressure conditions. In this paper, the RTCA DO-311 and RTCA DO-160 standards, which were created to ensure the safety and reliability of battery cells used in onboard equipment, are taken into consideration as they offer guidelines for the use of rechargeable battery systems onboard aircraft and provide test requirements for low-pressure conditions.

The following paragraphs highlight the testing requirements and procedures defined by the RTCA DO-311. A cost-effective experimental setup has been developed for this specific analysis to replicate and extend the environmental conditions required for the tests defined by the standards. The results of tests conducted on cylindrical and pouch cells in accordance with the standards are discussed. The paper concludes with a critical analysis of the standards and a discussion of improvements that could be made to the testing process.

Battery Characterization at Low-Pressure Condition

RTCA Test Procedures

Battery systems and cells in airplanes are frequently found in pressurized spaces. However, it is essential to design the systems with the awareness that cells must operate safely and dependably in the event of a rapid decrease of pressure within the aircraft.

RTCA provides technical performance requirements and guidance for the testing, certification, and use of equipment on board aircraft. The RTCA DO-311 standard provides minimum operational performance requirements and test procedures for rechargeable LIBs permanently installed on aircraft. The standard aims at ensuring that LIBs perform their intended functions safely under conditions encountered in an aeronautical environment. The RTCA DO-160 standard provides minimum environmental test conditions for the test procedures highlighted in the RTCA DO-311. Considering the effects of low pressure, two tests are included in the RTCA DO-311, the Altitude Test and the Rapid Decompression Test.

A reference Test (RT) is performed before and after each test to assess the cell's performance. An RT consists of a capacity test at 1C at Standard Temperature and Pressure (STP, 22 °C, 1 atm).

The Altitude Test (AT) aims to verify in a laboratory environment the safety of a battery cell in conditions that might be encountered by the aircraft during its operations. The test consists of the following steps:

1. Starting with a fully charged cell, reduce the absolute pressure over 15 min to an equivalent absolute pressure of 55,000 feet (0.09 atm);
2. Discharge the battery at 5C for 5 min;
3. Charge at a constant current until the maximum voltage for 3 hours;
4. Return to STP of the test area over 15 min;
5. Allow battery to stand for no less than 20 hours and no more than 24 hours on open circuit at 23 °C±2 °C.

As per the standard's evaluation criteria, the cell passes the AT if it does not show mechanical deformation, crack, or abnormal heating and the RT capacity is equal to the rated capacity.

The Rapid Decompression Test (RDT) aims to assure that seals and vent bands will quickly adjust pressure and reseal without allowing electrolyte to leak from the battery and that the batteries are not damaged in case the aircraft loses internal pressurization. The test's steps are the following:

1. Starting with a fully charged cell, adjust the absolute pressure to an equivalent altitude of 8,000 feet (0.74 atm) and allow the equipment to stabilize;
2. Reduce the absolute pressure to the equivalent pressure of 55,000 feet (0.09 atm) in 15 seconds;
3. Maintain this reduced pressure for at least 10 min.

As per the standard's evaluation criteria, the cell passes the RDT if it does not show mechanical deformation, crack, or abnormal heating and the RT capacity is equal to the rated capacity.

Experimental Test Set-up

To emulate high altitude circumstances, the aforementioned tests for energy storage systems and electronics for airborne equipment are typically conducted in altitude test chambers, which are environmental chambers with temperature and ambient pressure management. However, the system's complexity makes these chambers bulky and costly. In order to overcome these problems, a custom system that can replicate the necessary environmental conditions was designed and assembled using both commercial and custom-designed components (Fig. 1).

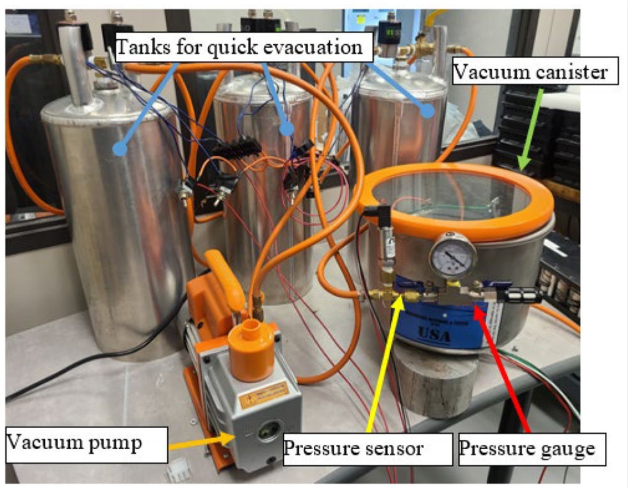
A vacuum canister with a 7.57 l volume that is sealed with a glass lid to allow monitoring of the test's activities serves as the testing environment. The chamber is evacuated using a commercial 1/3 hp vacuum pump, which can reduce the testing pressure to 0.04 atm. The evacuation system includes three tanks connected parallel, each measuring 11.57 liters, which are connected between the pump and the chamber. Solenoid valves are used to release the pressure sequentially, allowing the previously vacuumed tanks to quickly vacuum the chamber. The chamber can be evacuated using the suggested setup in 30 seconds for the RDT.

A manometer and a pressure sensor (Omega PX319-015A5V) are included in the data acquisition system to monitor the absolute environmental pressure in the chamber in real-time. The electrical connections needed to measure the cell's current, voltage, and temperature of the battery surface are brought inside the canister using pass-through fittings.

A state-of-the-art battery cycler from Arbin Instruments is used to charge and discharge the battery cell during the testing. The cycler is equipped with an auxiliary unit to acquire and log the data from the sensors and the thermocouples. The data are logged at 10 Hz.

The system is equipped with two thermocouples, one thermocouple is placed on the cell center to measure the cell's surface temperature, and the second thermocouple is used to measure the ambient temperature.

FIGURE 1 Picture of the experimental Test Set-up



Result

Commercial Off-The-Shelf (COTS) LIB cells come in different formats, shapes, and chemistries. For this study, two different cell formats were considered, a cylindrical cell, and a pouch cell. The specifications of the cells are listed in Table 1. Table 2 summarizes the tests performed on the battery cells, this section shows the experimental results achieved during the AT and RDT of the given cells, highlighting the cell's performance comparison achieved during the RTs performed before and after the referenced tests. The RT consists of a capacity test conducted at 1C for the cylindrical test and C/3 for the pouch cell.

Altitude Test Results

The AT was performed for both the mentioned cells using the test setup explained earlier. The cylindrical cell was tested at an equivalent absolute pressure of 55,000 feet (0.09 atm), and the discharge at low pressure was performed at 2.8C, which is the maximum discharge rating of the cell. Following the low-pressure discharge, the cell was rested for 60 min and charged at C/3 for 3 hours. Fig. 2 summarizes the results of the AT showing voltage, current, temperature, and ambient pressure. Table 3 summarizes the measured capacity of the cells in the different phases of the test.

TABLE 1 Specifications of the battery cells.

Form factor	Cylindrical	Pouch
Chemistry	LMO/Graphite	NMC/Graphite
Energy density [Wh/kg]	259	260
Capacity [Ah]	3.5	12
Max/Min Voltage [V]	4.2/2.5	4.2/2.7
Max. Cont. Current	2.8C	2C
Weight [g]	47	173

TABLE 2 Test matrix.

Test	Cylindrical	Pouch
Reference test	x	x
Altitude test	x	x
Reference test	x	x
Rapid decompression test	x	
Reference test	x	

FIGURE 2 Altitude test: voltage, current, temperature, and pressure for the cylindrical cell.

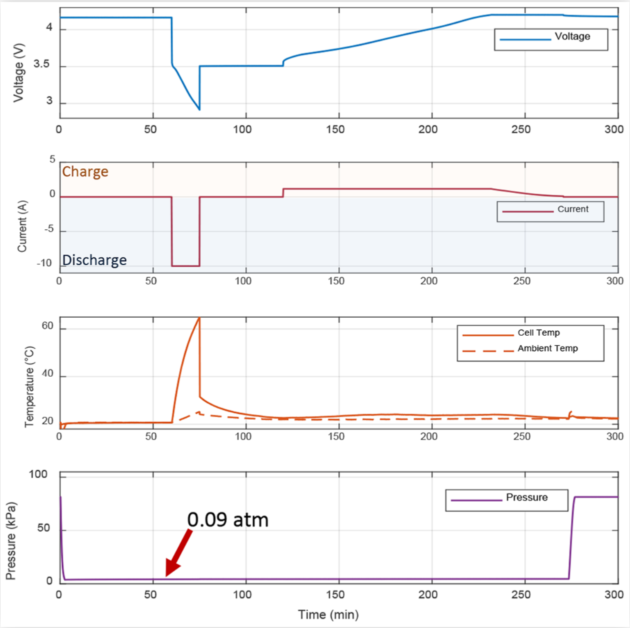


FIGURE 3 Altitude test: voltage, current, temperature, and pressure for the pouch cell.

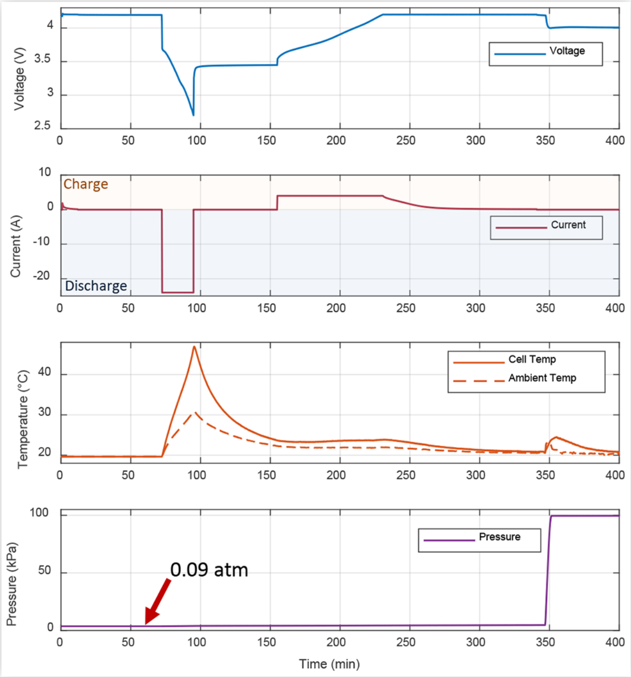


TABLE 3 AT Summary AT Results

Cylindrical cell		
	Capacity @ 1C [Ah]	**Capacity @ 2.8C [Ah]**
RT	3.2	3.05
AT	-	2.499*
RT	3.19 (Pass)	3.07
Pouch Cell		
	Capacity @ C/3 [Ah]	**Capacity @ 2C [Ah]**
RT	11.4	10.75
AT	-	9.13*

The cylindrical cell successfully passed the AT based on the standard's evaluation criteria, the cell did not show any mechanical deformation or crack. The RT performed after the AT showed a decrease of 0.3% in capacity compared to the previous RT. However, the capacity available in the 2.8C discharge during the AT showed an 18% decrease compared to STP conditions due to the high temperature reached during the test caused by the lower convection in vacuum.

The pouch cell failed the AT (Fig. 3) due to significant swelling during the test at low pressure. RT at C/3 performed after the AT showed significantly lower capacity (26% lower), as shown in Table 3. The capacity test at 2C in vacuum resulted in a 15% lower capacity attributable to the rise in temperature and structural damage caused by the cell swelling. It is important to mention that no mechanical constraints were applied to the cell during the test, as required by the RTCA DO-311 standard.

The timing difference for the AT performed on the cylindrical and pouch cell was because, despite the pouch cell being discharged at a lower C-rate, the capacity loss in percentage resulted to be significantly higher compared to the cylindrical cell.

Rapid Decompression Test Results

The cylindrical cell passed the RDT as well with no mechanical or structural damage to the cell case. The RT capacity test before and after the test showed no reduction in capacity. Table 4 compares capacity before and after RDT.

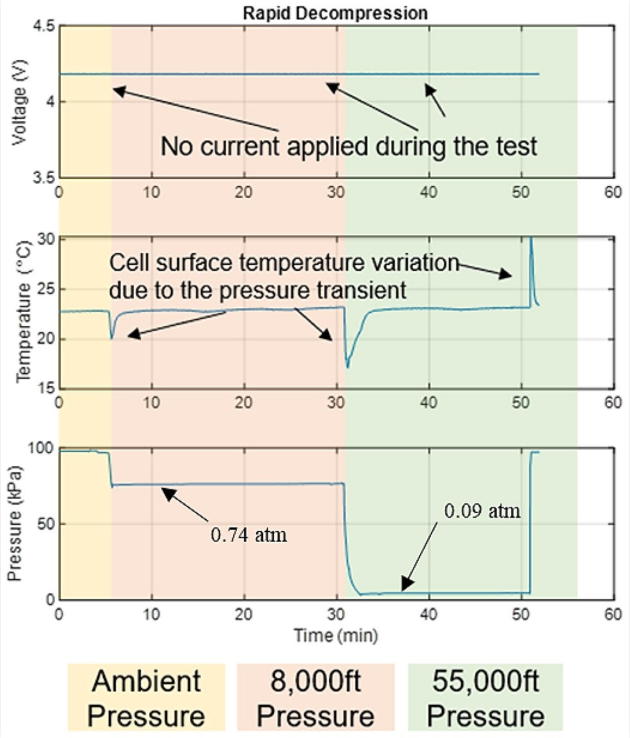
The voltage, temperature, and pressure evolution during the test are shown in Fig. 3; the test does not need discharging the cell, so the voltage remained constant during the test. The ambient pressure is initially reduced to 0.74 atm, then rapidly reduced to 0.09 atm when the system has stabilized. Despite the fact that the standard requires 15 seconds to accomplish the pressure change, the system took roughly 30 seconds to reach the pressure of 0.09 atm, due to hardware limitations. Since the pressure shift occurs quickly, the air temperature drops, which is mirrored by the cell's surface temperature; the temperature successively returns to equilibrium.

Considering the significant cell swelling seen during the test, and the low capacity measured during the AT and the

TABLE 4 Rapid Decompression Test Results

Cylindrical Cell	Capacity @ 1C [Ah]
RT (before)	3.2
RT after RDT	3.2

FIGURE 3 Rapid decompression test: voltage, temperature, and pressure for the cylindrical cell.



RT that followed, no RDT was performed on the pouch cell. Safety concerns were raised, due to the mechanical stress applied to the cell during the rapid evacuation of the cell. Potential cell failure can lead to electrolyte leaks and potential thermal runaway.

Conclusions and Future Work

The paper analyzed the RTCA standards reporting the relevant testing procedures LIBs in low-pressure environments, a custom-designed experimental design is explained, and results from the experimental campaign are shown. The study showed that cylindrical cells do not suffer a significant loss in performance in the case of altitude tests and rapid decompression tests proposed by the RTCA DO-311 standard. However, the thermal management system plays a fundamental role in keeping the system safe and efficient at low pressure due to reduced convection. The pouch cell shows significant swelling that resulted in a permanently damaged cell and might result in electrolyte leak and related safety hazards. The RTCA DO-311 standards were developed to test onboard battery equipment (nominal voltage 28V) that is typically used for backup power and does not consider larger systems that would be required for battery-powered propulsion.

- The standards require not adding additional mechanical and/or temperature constraints resulting in a non-satisfying performance of the pouch cell, and lower performance of the cylindrical cell during the AT. The requirement of a 5C discharge current during the AT is not always possible, because as seen not every cell can provide that level of performance, ignoring the characteristics and capabilities of the different chemistries.
- The standards also require that the capacity assessment be 100% of the initially rated capacity, a requirement that is not suitable with LIBs.

Given the paper's criticisms, future research in this area will involve an improved testing setup that includes temperature control of the cell's surface as well as the ability to monitor cell pressure changes during the test. The novel approach will allow distinct cells to perform best under the needed boundary conditions while adhering to the same mechanical and thermal restrictions as a pack condition. The results from these tests will provide insight into the requirements for using pouch cells under low-pressure conditions. However, testing under these conditions falls short of meeting all the requirements of the standards, but they could provide guidance on engineering novel test procedures for cells and battery packs for propulsion applications.

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Definitions/Abbreviations

LIB - Lithium-Ion Battery
LEO - Low Earth Orbit
RTCA - Radio Technical Commission for Aeronautics
SAE - Society of Automotive Engineers
UN - United Nations
IEC - International Electrotechnical Commission
UL - Underwriters Laboratories
STP - Standard Temperature and Pressure
AT - Altitude Test
RT - Reference Test
RDT - Rapid Decompression Test

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