Environment Test Campaign of A Commercial-off-the-shelf Electrical Double Layer Capacitor for Space Use

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In spacecraft development, high performance and reliability are key drivers for the development of satellite bus. For the electric power sub-system, electric double layer capacitors (EDLC), as energy storage, are good substitutes to the traditional battery systems during periods of solar outage. On orbit, power is fundamental for ensuring satellite performances and batteries related shortcomings can be a drag to ensure satellite power supply. However, EDLCs have the capability of operating under a wide temperature range and performing for a very high number of charge/discharge cycles, which results in accruable benefits to the missions on board the satellite.

Key Words: energy density, thermal cycle, spacecraft, vibration

1. Introduction

Electric double layer capacitors are capacitors with capacitance value in the kilo farads order, which is much greater than capacitance of commonly known capacitors in the market. Moreover, EDLCs present high capacitive density that makes them well-suited for applications hitherto meant for batteries. Since EDLCs are not originally designed for space environment, tests were carried out to affirm EDLCs survivability to space environment conditions.

For this research, EDLC **BCAP3400 P285** manufactured by Maxwell technology was used during environment testing. To ascertain the durability of the cell to the harsh space environment, functional tests were recorded before and after the durability exposure of the cell. The EDLC underwent the following testing:

- Vibrations test
- Long term test
- Thermal cycle test
- Vacuum test in room temperature

This paper presents the functional performance of EDLC before and after durability tests and the operating performance during long term, thermal cycle, and vacuum conditions.

By projection to 2025, the gravimetric and volumetric energy densities are estimated to become greater than 12Wh/kg and 16Wh/l, respectively.

A simply designed charged circuit was used for the implementation of charging /discharging cycles test for EDLC under various environment conditions .See figure 1

2. Test Set Up

For the purpose of this research, a DC power source to simulate the solar cells and power profile was used. The DC power source was connected to the to the EDLC and to the electronic load (E-load) with diode in between.The LabVIEW program operates for voltage based control (from 0.5V to 3.15V charging condition and 3.15V to 0.5V of discharging condition, which for low earth orbit (LEO) corresponds to a total controlled time of 100 minutes with 65 minutes of sun availability and 35 minutes of dark period).The time control was used to perform simulation/emulation of LEO orbit performance while the voltage control approach was used to perform the post durability functional tests. The functional test was conducted before vibrations test and the post functional test was conducted at the end of vibrations test, long term test, temperature variations test (high and low temperature conditions), or vacuum test. The durability tests were performed using vibrations machine, vacuum chamber, and thermostatic chamber.

Table 2 shows the specifications of the EDLC cell used for the tests. This EDLC cell is a COTS component and its development did not take into account its utilization in space environment. During the entire testing carried out, there was no padding done to partially or fully shield the EDLC from environmental damage.

Table 2. Specifications of the EDLC

Specifications	**BCAP3400 P285**
Rated Voltage [V]	2.85
Capacitance [F]	3400
ESR [mΩ]	**0.28**
Specific Energy density [Wh/kg]	7.34
Rated Operating temperature range [°C]	-40~65

Figure 1 shows the common test schematic for the charge/discharge simulation. The red dotted line was applicable while the test article was in chamber (thermostatic or vacuum).

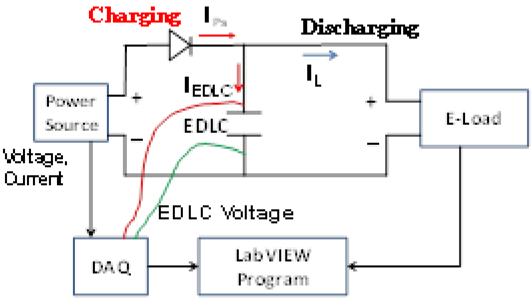

Figure 1. Charge/discharge cycling schematic for EDLC operation

An overview of the test conditions are given in Table 3.

Table 3. Charge/discharge test conditions

Orbital period condition	
Condition	**Period [seconds]**
PS cut-off supply (eclipse simulation)	2100
PS supplies power (sunlight simulation)	3900
Eclipe + Sunlight	6000

No.	EDLC temp. [°C]	Load	Environment
1	68	Constant current (2A)	Thermostatic Chamber (TC)
2	-37	Constant current (2A)	TC
3	-47	Constant current (2A)	TC
4	Room temperature	Constant current (2A)	Vacuum Chamber
5	Room temperature	Constant current (2A)	Atmosphere

Table 4 shows the specifications of the thermostatic chamber. The operating temperature used for the test were 68^{o}C, -37^{o}C, and -47^{o}C at a minimum soak time of 24 hours each.

Table 4. Thermostatic chamber specifications

Item	Specifications	
Thermostatic chamber	900 series – 925E-1-4-0-120	Manufacturer: Despatch Industries
	Test volume	0.02m^3
	Temperature range	-190˚C to 200˚C
	Power	2.392kVA
	Heater	2000W at 17.4A

For the creation of LEO environment vacuum condition under room temperature, a small vacuum chamber was used, which specifications are given in Table 5.

Table 5. Vacuum chamber specifications

Item	SUS304
Size	Total Length:100cm, Diameter 30cm
Ultimate vacuum	1.0×10^{-5}Pa ~ 1.0×10^{-3}Pa
Temperature	-150°C ~ 150°C
Thermal Input	Nothing: Cold = Shroud, Hot = Sheet heater Rail exist: Cold = Shroud, Hot = IR Lamp
Measure	K-Type Thermocouple (10CH)

For the functional tests carried out during or before the long-life testing, the power source was ON to charge the EDLC continuously under constant current-constant voltage (CC-CV) mode until the EDLC was charged to 3.15V (the controlling voltage value for power source to stop power supply based on the LabVIEW program), the supplying current to the EDLC from the power source here referred as I_{ps}, which is the EDLC current (I_{EDLC}) in the charging stage. From this point, the EDLC discharged directly to the load at constant current of 2A (at this stage the I_{EDLC} was equal to load current, I_L until the voltage drops to 0.5V (the set value to trigger ON the power source for charging condition).

For the long-life testing, the power source was ON to charge the EDLC continuously under constant current-constant voltage (CC-CV) mode until the EDLC was charged to 3.15V (the controlling voltage value for power source to stop power supply based on the LabVIEW program). From this point, the EDLC discharges directly to the load at a constant current of 2A until the voltage drops to 0.5V (the set value to trigger ON the power source for charging condition and trigger "standby mode" for the electronic load).Table 6 shows the controlling condition.

Table 6. Test conditions voltage controlled

Power source condition	**EDLC status**	**Load status**	**LabVIEW logic voltage setting**
PS supplies power (sunlight simulation)	Charge	Standby	0.5V to 3.15V
PS cut-off supply (eclipse simulation)	Discharge	1A/CC mode	3.15V to 0.5V
PS supplies power (sunlight simulation)	Charge	Standby	0.5V to 3.15V
PS cut-off supply (eclipse Simulation)	Discharge	2A/CC mode	3.15V to 0.5V

Random vibrations at an excitation level of 25Grms were imposed onto the EDLC cell. The test schematic of the random test is shown in Figure 2. Figure 3 shows the target PSD pattern applied to the jig. The base vibration was 25Grms and applied in the axial and transversal direction for 110 seconds, each. See table 7 for the vibration machine specification.

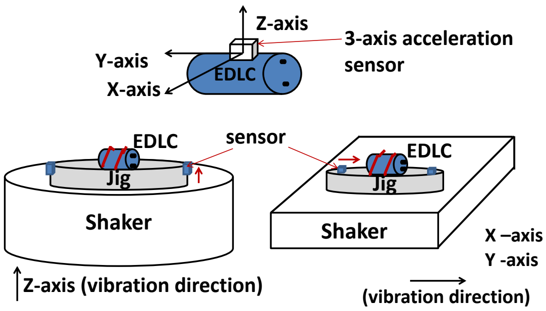

Figure 2. Sensors positions and vibrations directions

Table 7. Vibrations machine specifications

Table size	500×500mm
Maximum acceleration force	Random: 28 kNrms
	Sine: 35kN
	Shock: 87 $kN_{0\text{-}p}$
Maximum acceleration for no-load	Sine: 106G
	Shock: 147G
Direction	3 axis

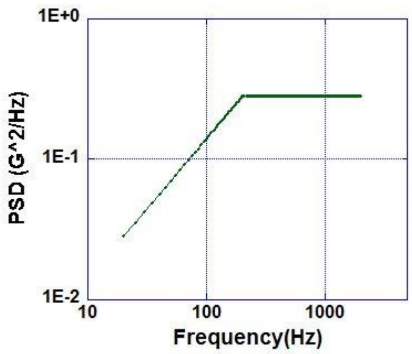

Figure 3: Input PSD for vibration

3. Test Results

The graph in Figure 4 shows the result of the first functional test prior to the first durability test for which the charging time was 65 minutes and discharging time was 35 minutes for the sunlight and eclipse periods, respectively.

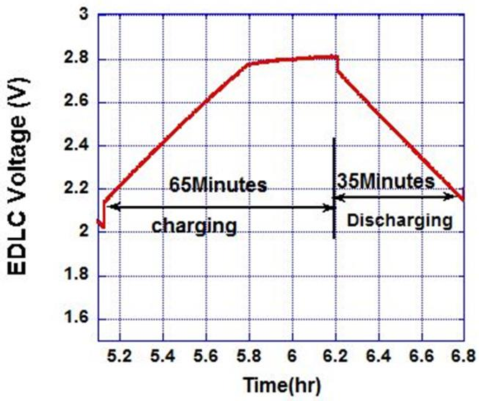

Figure 4. First functional test

knowing the voltage drop, instantaneous charging and discharge currents the internal resistance where calculated thus:

$$\rho = \frac{V_d}{i_c - (-i_d)} = 0.061\Omega$$

Where ρ is internal resistance, V_d is instantaneous voltage drop (V), i_c is the instantaneous charging current (ampere) and i_d is the instantaneous discharge current (ampere).

Charge, q is thus calculated

$$q = \int_{3900s}^{6000s} (i)dt = 2100C$$

And the available capacitance is

$$C_{available} = {}^{q}\!/_{\Delta V} = 3529\mathrm{F}$$

where ΔV is the difference of voltage from the beginning to the end of discharge.

$$C_{available} = 3400(+3.8\%)$$

3.2 Thermal cycle test in atmosphere

Table 8 shows the performance of the EDLC cells at +68°C, -37°C, and -47°C.

Table 8. Summary of durability performance

Test Condition	Capacitance [F]	Internal resistance[Ω]
+68°C	3309	0.075
-37°C	3338	0.102
-47°C	3341	0.110

3.3 Vacuum test in atmosphere

Table 9 shows the performance of EDLC in vacuum and atmosphere under room temperature. There was no effect of vacuum on the performance.

Table 9: comparison of EDLC under vacuum and in atmosphere at room temperature

Test condition	Capacitance [F]	Internal resistance [Ω]
Vacuum at room temperature	3605	0.071
Atmosphere at room temperature	3602.5	0.069

3.4 Long Term Testing

Figure 7 shows the first and last charge/discharge cycle of the long term test where, in each case, the EDLC was charged to 3.15V and discharged to 0.5V at a constant current of 2A. The first cycle spanned for about 2.28hours and the last cycle spanned within 2.27hour.

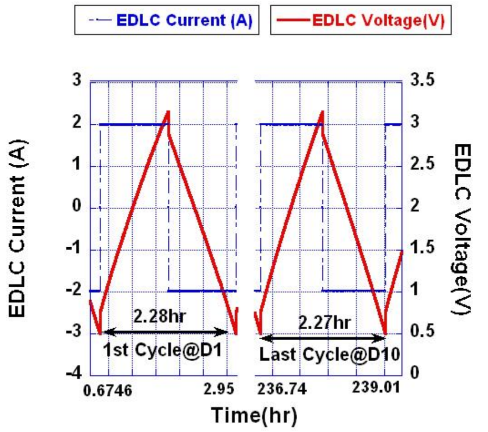

Figure 7. First and last cycle of the long term test

From Figure 7, it can be concluded that there is consistence of the EDLC performance when operated under the same conditions. Consistence of the pattern flow after 230 hours of non-stop operation from the first cycle could also be observed. For the performance of the first cycle of the long term durability test, a capacitance of 3434F, a charge of 8208C, and an internal resistance of 0.065Ω were recorded, while for the last cycle, a capacitance of 3434F, a charge of 8208C, and an internal resistance of 0.065Ω were recorded.

3.5 Vibrations Testing

Figure 8 shows the acceleration levels response of the EDLC. The resonance frequencies were 219Hz, 477Hz, and 258Hz in the X,Y, and Z vibration direction, respectively.

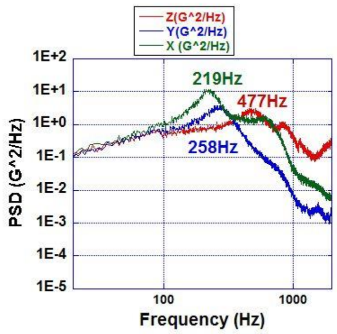

Figure 8. PSD response of EDLC at random vibration in X,Y, and Z direction

Table 10below summarizes the capacitance and internal resistance values before and after each durability test.

Table 8. Summary of EDLC after durability test

Timing	Charge[C]	Capacitance [F]	Internal resistance [Ω]
Pre-vibration	2100	3529	0.061
Post Vibration	2100	3560	0.065
Post -long life	8193	3413	0.061
Post-thermal cycle	2100	3480	0.065
Post vacuum	1441	3602.5	0.07
Post radiation	2100	3540	0.065

4. Conclusions

In conclusion, series of environmental tests were carried out on COTS EDLC. The results of high temperature (+68^{o}C), room temperatures, low temperature (-37^{o}C, -47^{o}C), and vacuum tests showed no serious performance degradation of the EDLC in those environment. Long term, vibrations, and shock tests were also conducted. The results of the EDLC post functional performance show the cell survived the test, which implies that it is robust. The overall conclusion is that EDLC is durable for space environment.

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