

Evaluation and Qualification of Commercial Off-The-Shelf Supercapacitors for Space Applications

2nd Space Passive Component Days (SPCD), International Symposium

12-14 October 2016

ESA/ESTEC, Noordwijk, The Netherlands

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INTRODUCTION

Supercapacitor is a product which fills the gap between batteries and capacitors, featuring very high power density (up to 100kW/kg) with lower stored energy than that of batteries (up to 7 Wh/kg).

This paper is focusing on small size supercapacitors enhancing power densities ≤ 15 kW/kg.

This technology is already widely used in various industrial, automotive and aeronautic applications.

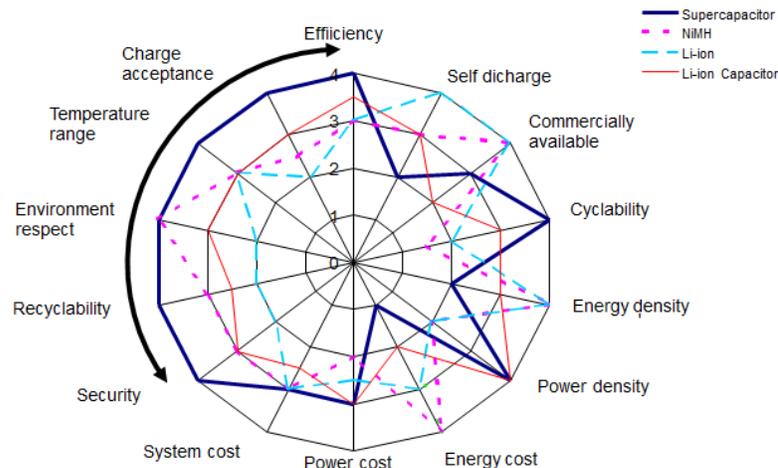


Fig. 1. Supercapacitor, a safe and efficient storage component compatible with large temperature ranges

Its fast charge and discharge time, its ability to withstand millions of charge / discharge cycles and its wide range of operational temperature (-40°C to $+70^{\circ}\text{C}$) makes it a perfect candidate for several space applications (launchers and satellites) as demonstrated in ESA Study Contract No. 21814/08/NL/LvH entitled “High Power Battery Supercapacitor study” completed in 2010 by Airbus D&S. From the most promising ones, it can be quoted: optimization of pyrotechnical activation system, high power mechanisms, electrical thrust vector control, high power radar supply or even hybridization of Supercapacitor banks with Li-Ion batteries.

The number of known flight demonstration is very low. This is partially linked to the fact that there are currently no parts available at space grade.

EVALUATION OF SUPERCAPACITORS FOR SPACE APPLICATIONS

Components selected for evaluation

Several past studies such as ESA Study “High Power Battery Supercapacitor study” have demonstrated the interest of Commercial off the shelf (COTS) supercapacitors for space applications.

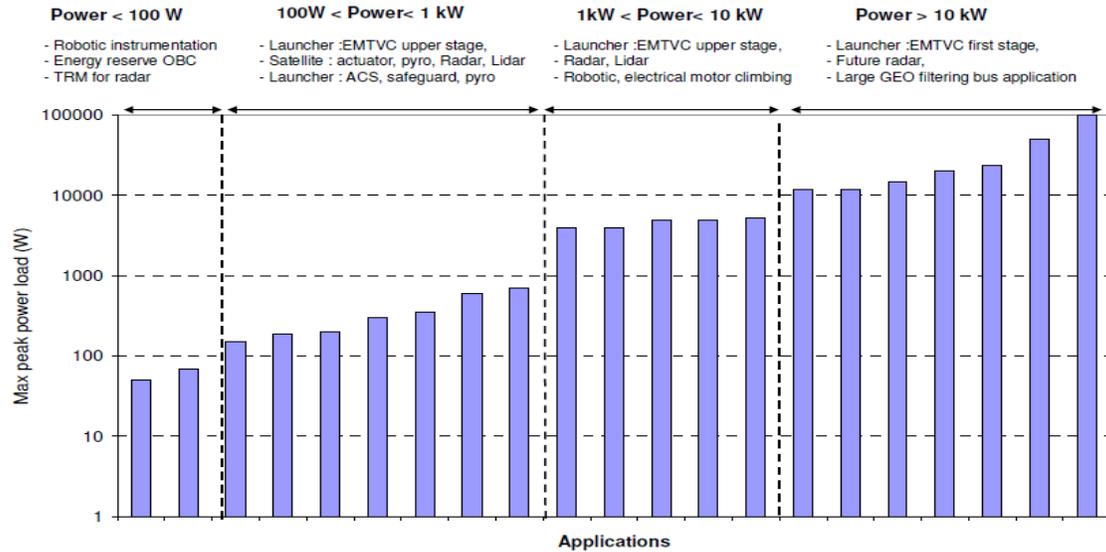


Fig. 2. Supercapacitor, a solution to a large number of space applications

From this activity, components with capacitance of tenth of Farad are identified to cope with the most promising applications.

Then, four commercial off the shelf (COTS) supercapacitors were evaluated: Cap-XX® HS130 (2.4 F), Maxwell® PC10 (10 F), Nesscap® EHSR 0010C0-002R7 (10F) and Maxwell®, BCAP0010 P270 was submitted for evaluation testing.



Fig. 3. The four tested commercial off the shelf supercapacitor types from left to right Cap XX® HS130 (2.4 F), Maxwell® PC10 (10 F), Nesscap® EHSR 0010C0-002R7 (10F), Maxwell® BCAP0010 P270.

The datasheet characteristics of the parts are described in the table hereunder:

	Cap XX® HS130	Maxwell ® PC10	Nesscap ® EHSR 0010C0-002R7	Maxwell ® BCAP0010 P270
Capacitance BoL	1.92F–2.88F	9F-12F	9F-12F	8F-12F
DC ESR BoL	< 31 mΩ	< 180 mΩ	< 34mOhms	< 80mOhms
AC ESR BoL	-	-	< 26mOhms	< 60mOhms
Rated voltage	2.75V	2.5V	2.7V	2.7V
Absolute Maximum Voltage	2.75V	2.7V	2.85V	2.85V
Maximum RMS Current	6A	-	-	-
Maximum Continuous Current @ ΔT = 15°C	-	2.4A	3.4A	2.2A
Maximum Continuous Current @ ΔT = 40°C	-	3.8A	5.6A	3.5A
Leakage Current	< 5μA	< 40μA	< 23μA	< 30μA

The details and results of these tests can be found in the technical notes of [1] and [2].

Technology analysis assessment

The following tests were performed on the parts.

- X-Ray inspection MIL STD 202 method 209
- External inspection ESCC2263000 issue2
- Dimensions ESCC2263000 issue 2
- Resistance of the terminals MIL STD 202 method 208
- Internal visual inspection

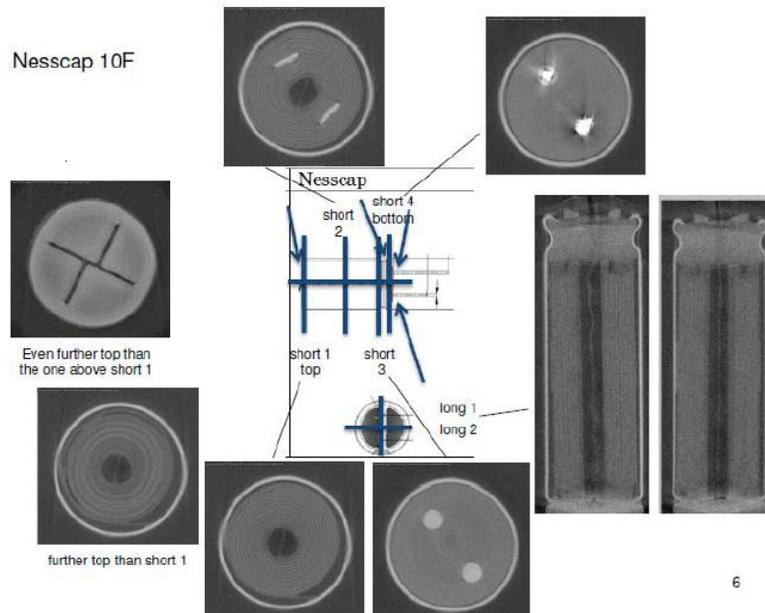


Fig. 4. X-Ray inspection on Nesscap EHSR 0010C0-002R7 (10 F)

Nesscap® and Maxwell® BCAP0010 P270 type has got the different assembly technology (winding one) than Maxwell® PC-10 and Cap-XX® (folded one). Both sides of the electrodes are covered with graphite. All the components use the same technology with the Graphite layers separated by semi permeable membranes and connected together by electrolyte. Maxwell® PC-10 type is not good in terms of negative electrode fixing. The minus pole is connected only by the touch to the alumina layer (unstable during thermo-mechanical stresses). The Nesscap® is good in terms of electrodes fixing on the alumina base layer (spot welded).

Generally, an additional fixture when used at unit level will need to be designed to ensure a good mechanical strength.

Mechanical and Thermal Tests

The following tests were performed on the parts.

- Fast temperature transients and vacuum exposure
 - o Fast temperature transients MIL STD 202 test method 107
 - o Vacuum exposure
- Radiation ESCC 22900
- Mechanical tests
 - o Seal test MIL STD 202 test method 112
 - o Vibration MIL STD 202 test method 204D
 - o Shocks MIL STD 202 test method 213

During vacuum and fast temperature transients exposures, no leakage of electrolyte have been identified.

The capacitance decreases due to the temporary partial loss of diffusion capacity and it's common to all manufacturers. The leakage current drops down by filling up deep states of capacitors by long time charging during the leakage

measurements (each step takes 72 hrs of charging). This feature is also very well known on even different types of capacitors (e.g. tantalum). The ESR increases by degradation of internal conduction of electrolyte-graphite system.

After thermal cycles and vacuum exposure, ESR increase of Maxwell® PC-10 is unacceptable.

The Cap-XX® unstable behavior should be explained by encapsulation technique used – soft body of the capacitor does not hold the capacitor in fixed position. The opposite behavior one can see on Maxwell® PC-10 equipped with solid outer body.

After the tests there was only a slight decrease of capacitance for all cells. The internal resistance only increased marginally. The leakage current decreased as expected.

For Cap-XX®, a capacitance increase assisted with ESR increase has been observed. The only one explanation we have found can be described by electrolyte diffusion into the deeper cavities causing the capacity increase, and two successive mechanisms can cause the ESR to increase. The first one is that the missing electrolyte drawing into cavities disappears from separation layer causing internal resistance between electrodes to increase. The second one should be caused by mechanical distance increase between electrodes induced by thermo-mechanical stress.

It has to be noted that Maxwell® BCAP0010 P270 was not submitted to fast temperature transients, vacuum exposure and radiation.

Floating life tests

Floating life test is a continuous exposure to a certain voltage at a certain temperature. The purpose of this test was to demonstrate the suitability of the cell operating voltage and temperature range and to find the best conditions to improve lifetime. The pass / fail criteria selected are capacitance change < 20% from initial value and ESR change < 100% from initial value.

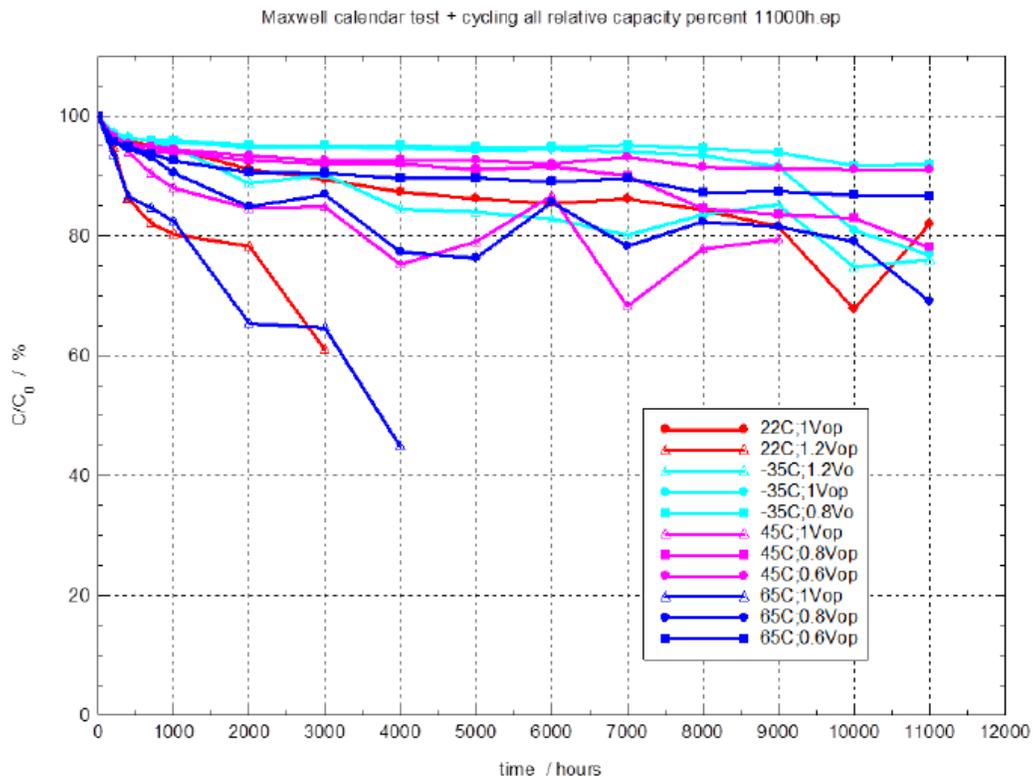


Fig. 5. Capacitance evolution during floating life test on Maxwell® PC10

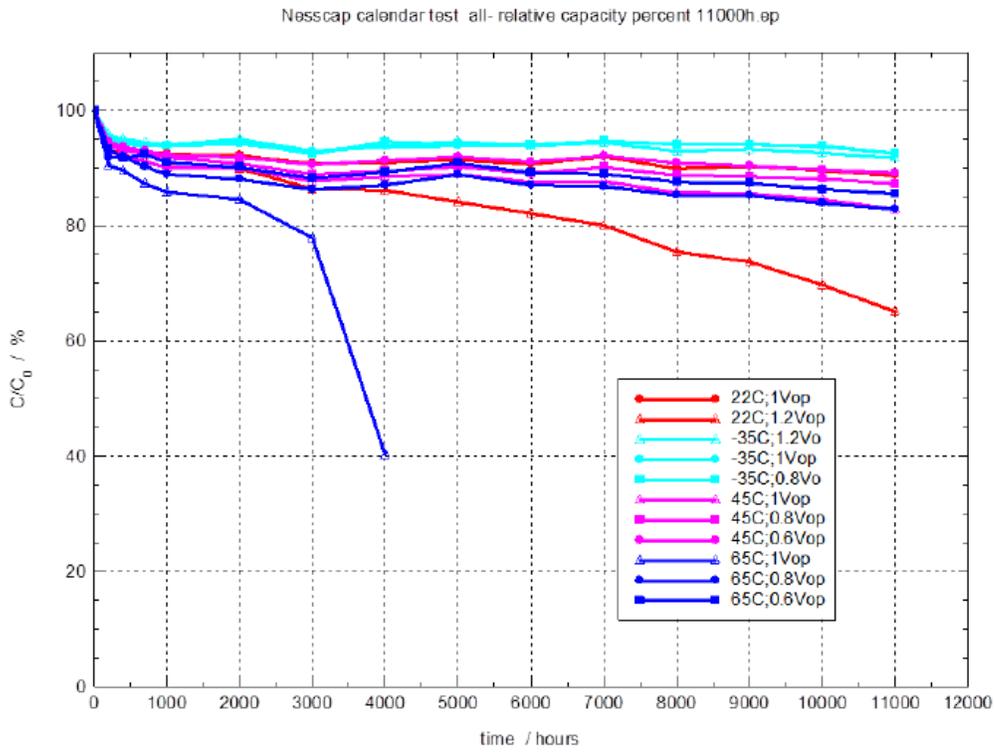


Fig. 6. Capacitance evolution during floating life test on Nesscap® EHSR 0010C0-002R7

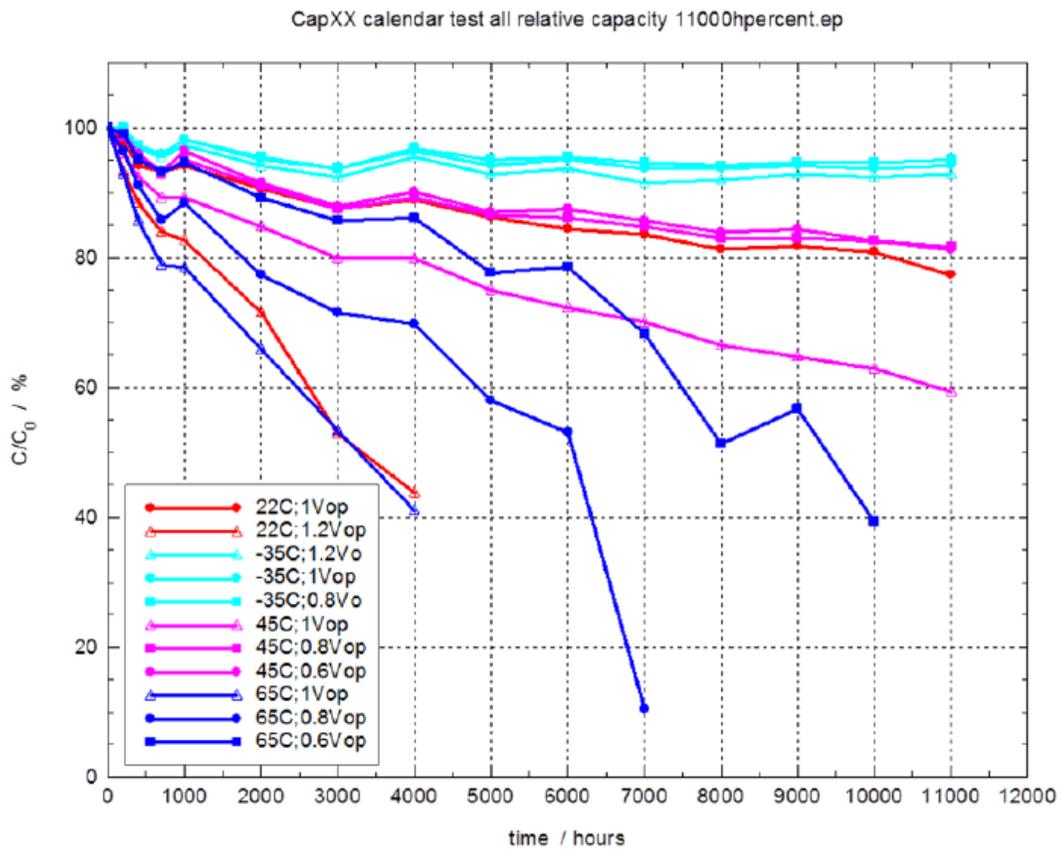


Fig. 7. Capacitance evolution during floating life test on Cap-XX® HS130

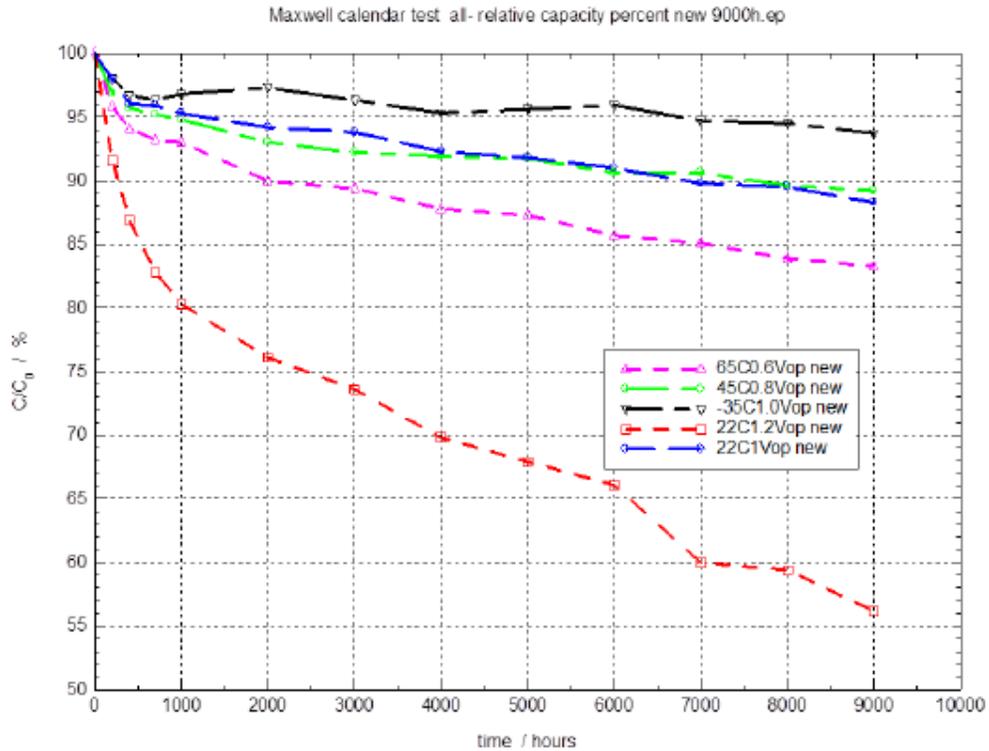


Fig. 8. Capacitance evolution during floating life test on Maxwell® BCAP0010 P270

The floating life performed at different voltages and temperature shows close relation between them. Higher voltage at higher temperature leads to an earlier failures. The failure mechanism background shall be assign to electrolyte decomposition.

The best endurance results were obtained for Nesscap, the second place takes Maxwell® BCAP0010 P270, then Maxwell PC10® and the last one is Cap-XX®.

From the leakage current one can see the higher initial values caused by filling of internal charge states. Looking at the Maxwell® PC-10 samples at the 65°C it's clear that the current increases before they die.

Generally, a strong degradation is observed for floating life tests at 65°C with an operating voltage superior to 0.6 Vop and floating life tests at 20°C with an operating voltage superior to 1.2 Vop. The optimal conditions are with an operating voltage lower than 0.8 Vop and temperature range is between -35°C and 45°C

Cycle life tests

The purpose of this test was to demonstrate the suitability of the cell submitted to three voltage cycling conditions: 100% continuous cycling (between 0V and Vop), 75% discontinuous cycling and 75% continuous cycling at certain temperature.

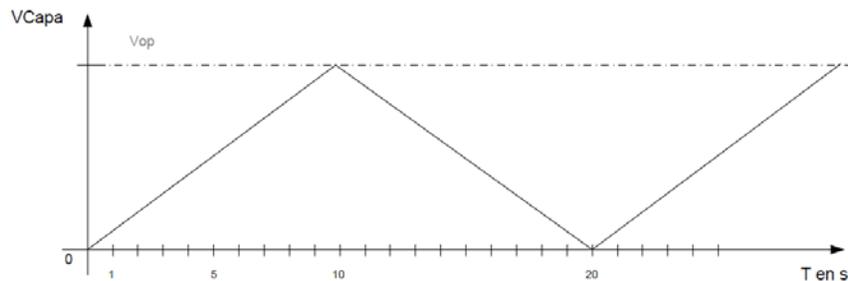


Fig. 9. 100% continuous energy cycling.

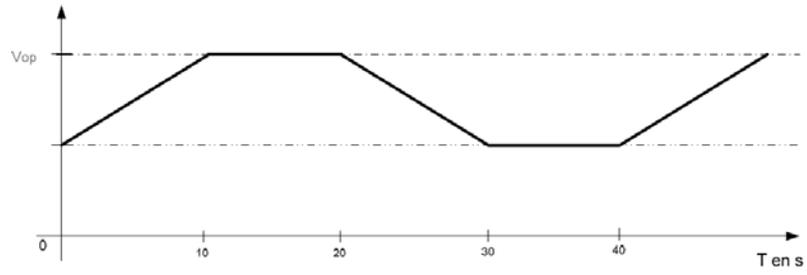


Fig. 10. 75% discontinuous energy cycling.

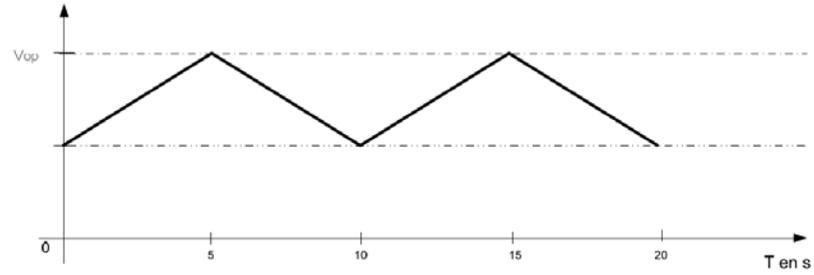


Fig. 11. 75% continuous energy cycling.

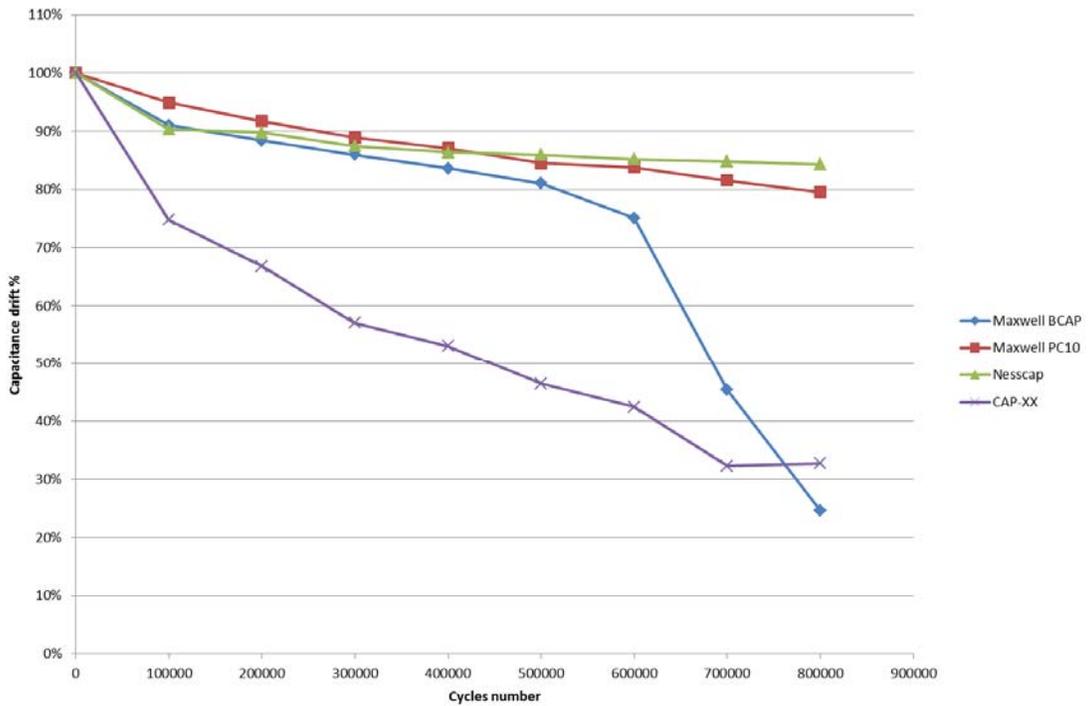


Fig. 12. Capacitance evolution during 100% continuous energy cycling

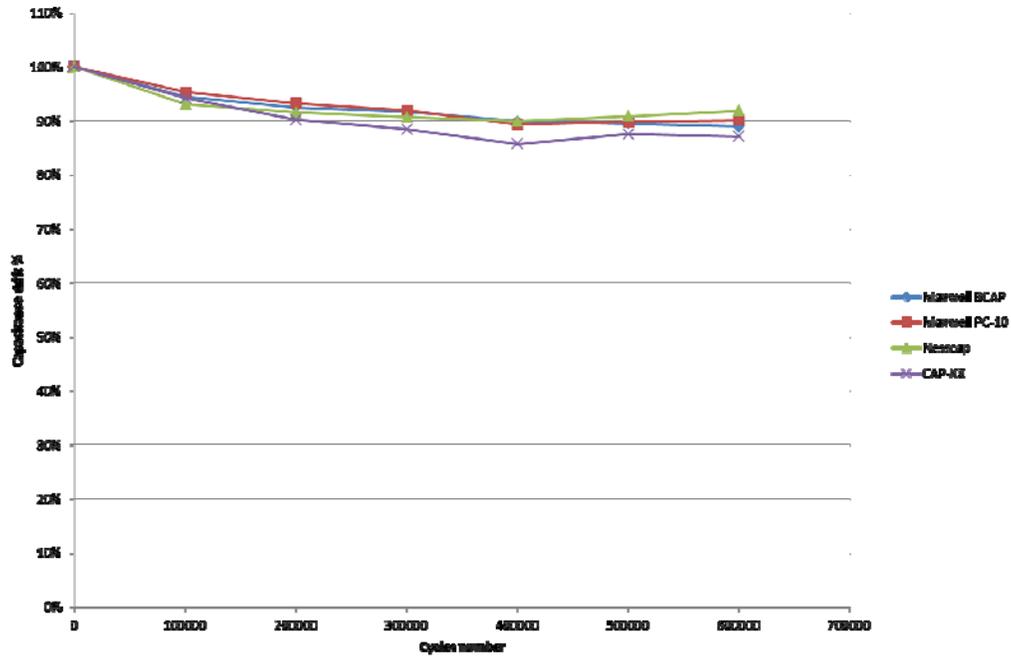


Fig. 13. Capacitance evolution during 75% discontinuous energy cycling

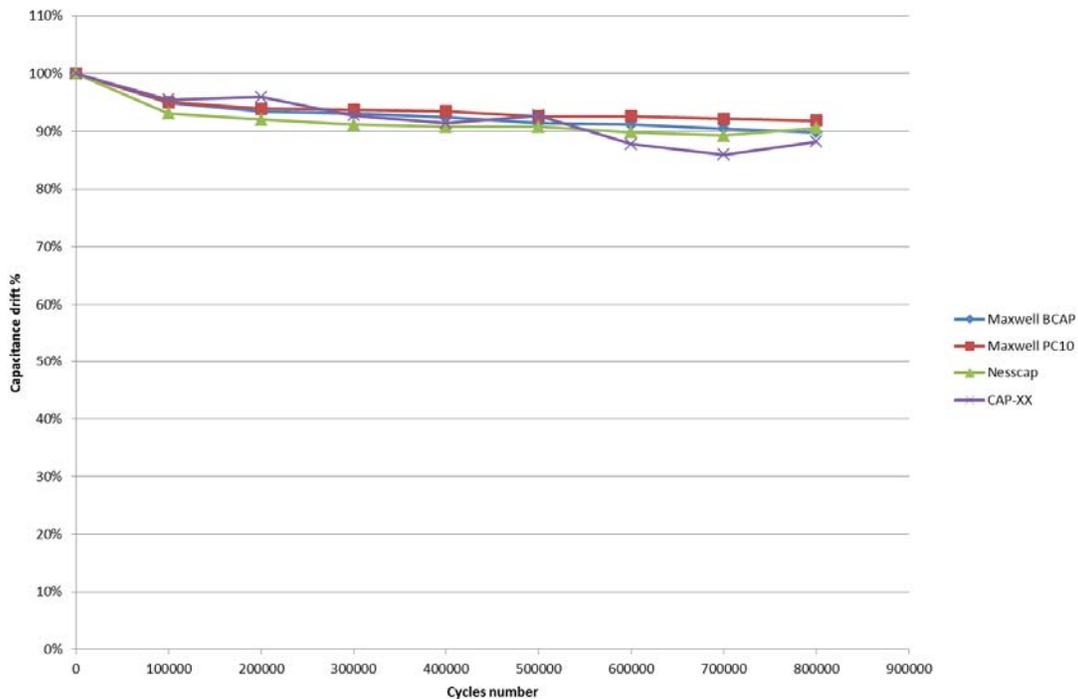


Fig. 14. Capacitance evolution during 75% continuous energy cycling

The 100% continuous cycling is the hardest test in this set of tests. Nesscap® did not show any issue up to 800 k cycles. From DC measurement on Maxwell® PC10 after cycling, nothing suspicious can be found. But during the cycling, the supercapacitors were loosening their internal connection due to higher temperature and showing capacitance almost equal to zero and very high values of ESR. Cap-XX® capacitors survived only about 200 k cycles, then Capacity goes down and ESR up without recovery (electrolyte worn out). Maxwell® BCAP0010 P270 failed at 400 000 cycles with an ESR higher than 200 % of the Initial value.

The 75% discontinuous cycling is the weakest test in this set of tests, because the supercapacitors can relax within each cycle and cool down. Nesscap®, Maxwell® PC-10 and BCAP0010 P270 as well as Cap-XX® did not show any issue up to 600 k cycles.

The 75% continuous cycling is the second hardest test in this set of tests. Nesscap®, Maxwell® BCAP0010 P270 and Cap-XX® did not show any issue up to 800 k cycles. As for 100% continuous, Maxwell® PC-10 seems OK from the DC measurements but during the cycling the supercapacitors were loosening their internal connection due to higher temperature and showing capacitance almost equal to zero and very high values of ESR. When they are left to cool down the cells recover their internal connection and show nominal performance. This behavior gives rise to additional risks like local overheating that could lead to internal pressure increase and then cell opening. This feature appears even after 40k cycles.

Generally, a strong degradation is observed with continuous cycling for 100% energy. The optimal cycling condition is inferior to 75% energy.

It has to be noted that Maxwell® PC-10 and BCAP0010 P270 are the the most heating devices caused by the ESR values. This is mainly visible on continuous cycling, in which cooling (rest) section is missing.

Abusive tests

Abusive testing were performed in order to identify potential hazards:

- Overheating : 10 samples of each reference were placed at temperature of 90°C and constant voltage equal to Vop during 168 hrs.
- Short circuit : 10 samples of each references were submitted to 10 successive short circuits from a voltage equal to Vop and at room temperature 22° +/- 3C.
- Overcharge : 10 samples of each references were submitted to 100 overcharge cycles at a voltage equal to 1.5 * Vop and at room temperature 22° +/- 3C.
- Overdischarge : 5 samples of each references were submitted to 100 overdischarge cycles from voltage equal to Vop until -1.5V and at room temperature 22° +/- 3C.
- Peak current: 1 sample of each reference was submitted to 1000 peak current cycles (with 1 minute rest time after each cycle to allow it cool down) charging and discharging at 10A between 0 and Vop at room temperature 22° +/- 3C.
- Ripple current
 - o 1 sample of each reference was submitted to charge and discharge at 3.8A current applied around Vop at least (7 days) at 10 Hz cycling frequencies
 - o 1 sample of each reference was submitted to charge and discharge at 3.8A current applied around Vop at least (7 days) at 100 Hz cycling frequencies

The overheating test was far too much for all three types of supercapacitors. The Cap-XX® exploded, Maxwell® PC-10 inflates, Nesscap® no visual change. All failed into open circuitry.

The 10Hz ripple current was too much for Maxwell® PC-10. The main reason for this failure is higher ESR of this supercapacitor technology, which resulted in higher temperature during the test causing faster degradation of electrolyte. The 100 Hz survival is very likely related to the ESR frequency dependency. At 10 Hz the ESR value is about 50% higher than at 100 Hz producing at the same current level 50% more heat.

From the capacitance point one can see the only overcharge test cause decrease by 10%, due to trapped change within internal diffusion layer speeding up charging time resulting in capacity drop.

The supercapacitors are generally not that much sensitive to the negative biasing (overdischarge) due to their bipolar structure.

The overcharge conditions can increase an ESR and decrease capacitance values by electrolyte ageing.

The test condition for peak current has a higher impact on Maxwell® PC-10 regarding to higher ESR.

It has to be noted that Maxwell® BCAP0010 P270 was not submitted abusive testing.

Vacuum life tests

As a complement of the evaluation activity, 10 Nesscap® 10F parts were submitted to life test under primary vacuum conditions (<10mbar) to check the long term compatibility of parts with space environments. The test was performed at Airbus D&S Toulouse electrical laboratory.

After 13 months, the ageing is similar to the one obtained at ambient pressure under the same temperature and voltage conditions.

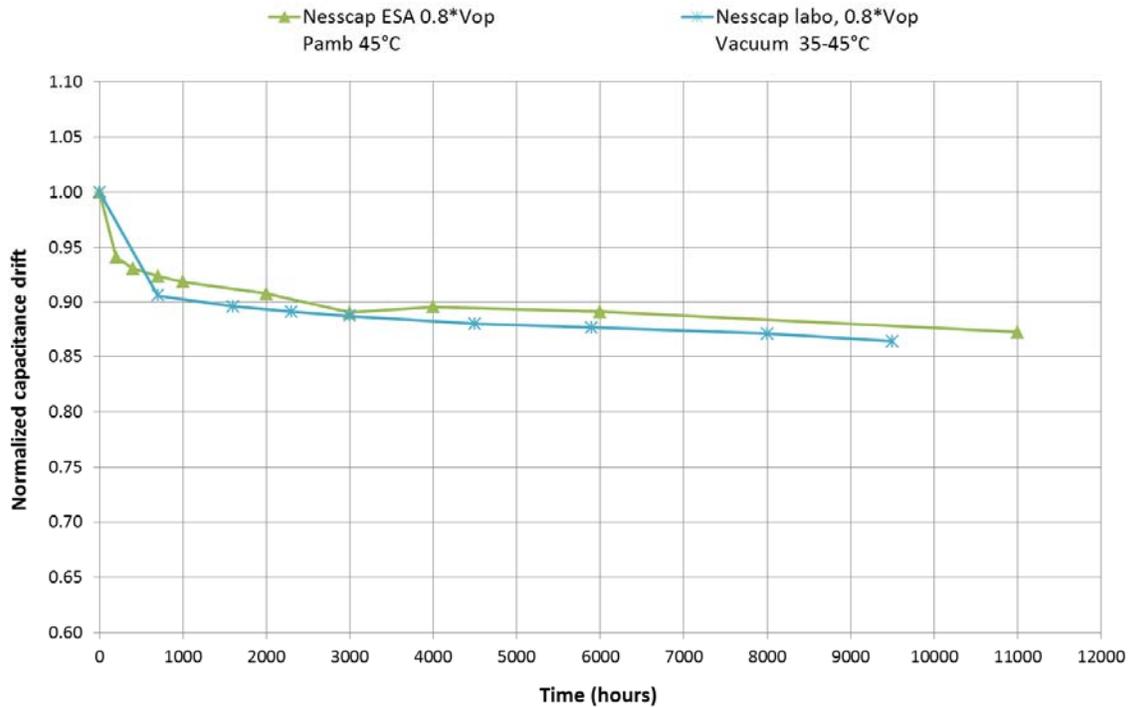


Fig. 15. Comparison between floating life test results on Nesscap® 10F under vacuum and ambient pressure conditions

Validation at unit level

In addition to the test performed at component level, a Bank Of SuperCapacitor (BOSC) based on Nesscap® 10F was designed, manufactured and tested [3]. The unit implement a parallel / series arrangement of the parts with passive balancing based on resistors.



Fig. 16. Illustration of Nesscap 10F Bank of SuperCapacitors

After testing, it has to be noted that no degradation observed after mechanical and thermal vacuum tests. After 3 000 000 electrical cycles at 45°C in 75% discontinuous energy cycling condition, a low degradation of the performance is observed :

- Less than 12% loss of capacitance
- Less than 25% increase in series resistance
- 20mV drift between the highest and lowest voltage (bank configuration).

Modelling

The results from the electrical characterisation and both floating and cycling life test have been processed to deduce electrical and ageing models of each references [4].

Recommended guidelines to improve lifetime

From this test campaign and especially life test results, the guidelines hereunder have been emitted:

- To apply a voltage derating lower than 85% of max rated voltage
- To apply an additional derating on supercapacitor voltage in order to avoid it to be permanently charged at max derated voltage.
For example to find solutions at system level to decrease supercapacitor voltages when not used during the mission.
- To limit the components temperature at 45°C (except limited transients up to 65°C).
- To store components under 0V and in cold condition (-10°C) before use.
- For electronics circuit design, a margin of 2 on ESR and capacitance values is recommended.

TEST CAMPAIGN OF 10F NESSCAP® SUPERCAPACITORS FOR THE ENTRY IN EPPL II

Components selected and frame of the activity

The evaluation study introduced in the previous chapter has demonstrated the interest and suitability of COTS supercapacitors for space applications. In particular, this activity has highlighted the excellent performances of the 10F components from Nesscap® in terms of ageing when submitted to life test and space environments including vacuum at both cell and system levels and enabled to identify the part as a good candidate for future space qualification.

Nesscap® is a company based in Korea which has manufactured for more than 10 years a wide range of high performances supercapacitors used in several industrial domains.

Nesscap® has improved the 10F part to enhance its sealing performances including urethane coating around leads, anodization of the lead part attached to the electrode and improvement of the rubber bung. This improved XP product was released to the general public (available in mass production) in April 2016 and will be maintained in production at least up to 2021. Moreover, in case of any change in the material, process or design of the part, Nesscap® will submit a PCN for approval.



Fig. 17. Nesscap® EHSR 0010C0-002R7UC (10 F)

The current on-going activity under ESA Study Contract No. 4000115278/15/NL/GLC/fk entitled “Generic Space Qualification of 10F Nesscap Supercapacitors” consists in two main activities. First to perform an official test campaign on Nesscap EHSR-0010C0-002R7UC parts in order to have the part introduced into ESA EPPL Part2. Second to develop and qualify the associated Bank Of SuperCapacitor, a generic and modular unit including components parallel/series arrangements compatible with several space systems.

Screening tests

In the frame of the activity, a batch of 3.000 parts of Nesscap® EHSR 0010C0-002R7UC has been procured.

The first step of the activity consists in parts screening.

- Visual inspection
- Initial characterisation
- Vacuum exposure
- Intermediate characterisation
- Burn-in
- Final characterisation

For that purpose, EGGO Space has developed specific test facilities so that to perform the screening of a 200 parts batch in one month.



Fig. 18. EGGO supercapacitors screening facilities - burn-in (left) and vacuum (right)

Currently 1000 parts passed the screening. Approximately 6% were rejected on visual inspection. The reason is bended leads due to soft packaging – 300 pieces in a bag. All parts succeeded in burn-in and vacuum testing.

Test campaign for the entry in EPPL II

The test campaign including the tests listed hereunder are foreseen

- Initial and final electrical characterization (80 parts)
 - o Capacity determination
 - o ESR measurement (DC and AC impedance)
 - o leakage current
- Technology analysis assessment (5 parts):
 - o External inspection ESCC2263000 issue 2
 - o X-Ray inspection MIL STD 202 method 209
 - o Solderability MIL STD 202 test method 208
 - o Dimensions ESCC2263000 issue 2
 - o Resistance of the terminals MIL STD 202 method 208
 - o Internal visual inspection
- Outgassing test (5 parts) : ECSS-Q-ST-70-02
- Mechanical and Thermal tests (10 parts)
 - o X-Ray inspection MIL STD 202 method 209
 - o Vibration MIL STD 202 test method 204D
 - o Shock MIL STD 202 test method 213
 - o Fast temperature transients MIL STD 202 test method 107
 - o Seal test MIL STD 202 test method 112
 - o Technology analysis assessment
- Life test (60 parts)
 - o Calendar test (success criteria @ 2000h)
 - 20 parts at $0,9 \cdot V_{op}$ and @ $50^{\circ}C$
 - 20 parts at $0,9 \cdot V_{op}$ and @ $60^{\circ}C$
 - o Cycle life tests
 - 20 parts at continuous 100% energy cycling
 - o Vacuum life test
 - 800 parts to be tested during 9000 h in floating life test under vacuum at $+55^{\circ}C$.

CONCLUSION AND FUTURE WORKS

The activities performed have demonstrated that COTS supercapacitors cells are suitable for space applications if they are operated in the derating conditions identified.

The next steps concern the completion of the test campaign on 10F NESSCAP® supercapacitors for the entry in EPPL II. Those results will be then analyzed to give a status on the suitability of the parts for space applications. If approved, a procurement specification at ESCC template will be issued, including the characteristics of the parts and the screening conditions to be applied for lot procurement and the process to have the part introduced in ESA EPPL Part II will be initiated.

In parallel, a bank Of Supercapacitors based on Nesscap® is under development and will be submitted to qualifications tests.

If successful, this study will allow having the Nesscap® 10F product space qualified and available on the shelf at both component and unit levels with a TRL level of 7. The completion of the proposed study will enable new applications or developments involving supercapacitors. The proposed study appears then to be of great interest for European space industry.

The targeted customers are prime contractors or equipment manufacturers that need either a complete BOSC (from CSRC) or only screened supercapacitors components (from EGGO).

This project will put into place a European industrial supply chain for supercapacitors products at space grade that will enable its utilization for space. It will also develop skills and facilities in space developments at both CSRC and EGGO Space levels, useful for this product and for future ones.

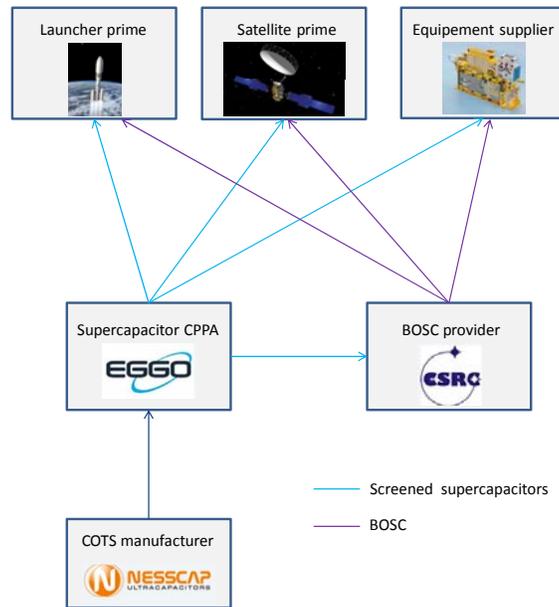


Fig. 19. Future industrial organization for Nesscap and BOSC procurement for space applications

In this paper it is aimed at providing an overview of what was and will be done in these programs for qualifying supercapacitors for the use in space applications.

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AUTHORS



Bertrand Faure received his diploma in Electrical Engineering at ENSEEIHT, Toulouse in 2006. He joined Airbus Defence and Space where he worked successively as electrical and power study engineer, electrical architect on sub-systems and energy storage engineer and project manager.



Dr. Petr Vašina received his diploma from the Technical University of Brno Faculty in Electro-Technology and applied physics. He is currently General Manager and Owner of EGGO Space Ltd. focused on Aerospace and Green Technologies. The company provides services in three main areas: Testhouse; Screen-Print and Recycling. He has been involved in projects such as development of test facility dedicated to passives components and management of test campaigns.



David Latif received his diploma from the Economy school in Lanškroun. He completed a NASA project management course in 2014. He joined the Company EGGO Space in 2012 and is currently project manager. He has been involved in several projects such as Evaluation of Supercapacitors and Impact at system level as a prime. He is currently working on High Density Connectors suitability to Space application ARTES 5.1 as prime.



Dr. Brandon Bürgler received his diploma in Material Engineering at the Federal Institute of Technology Zurich in 2002. After obtaining his PhD in Electrochemistry in 2006 he joined BMW Group where he worked on Fuel Cells, Supercapacitors and Batteries. He joined the European Space Agency in 2012 where he is working as Energy Storage Engineer.

Dr. Denis Lacombe was awarded a PhD degree in solid physic by the University of Toulouse in 1999 and he join Eurofarad (France) in the same year as process engineer. Starting from 2002, he worked in different positions in EADS Astrium (France). He joined ESA (ESTEC centre in Netherlands) in 2006 as component engineer in charge of passive component. He works on the ESCC qualification of EEE parts (passive components) and supports projects for the selection, procurement and failure analysis of these components.



Dr. Marek Simcak received his diploma in Electronic Devices and Systems at the Brno University of Technology in 1995, thesis was focused on Digital Signal Processing applications performed at ESIEE, Paris, France. After obtaining his PhD performed at IMEC, Leuven, Belgium, he co-founded Czech Space Research Centre (CSRC), where he worked as a manufacturing manager, a project manager, now acting as a managing director.