SUPERCAPACITORS FOR SPACE APPLICATIONS: TRENDS AND OPPORTUNITIES

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INTRODUCTION

2000

- First COTS supercapacitors
- Hybrid power studies for terrestrial applications
- First electrical characterization for space
- Inventory of high-power pulses needs for space

2008-2010

ESA studies:

- High Power Battery Supercapacitor systems study (ESA Contract No. 21814/08/NL/LvH)
- Graphene Enabled Supercapacitors Cell (ESA Contract No. ESA 4000112857/14/NL/PA)

2012-2017

ESA studies:

- Evaluation of supercapacitors at system level (ESA Contract No. 4000105661/12/NL/NR)
- Sources for high power/energy demanding devices for launchers (ESA Contract No. 4000105044)
- SpaceCap Stack Development to Market & Qualification Activity (ESA Contract No 4000119350/16/NL/Cbi)

2017-2022

ESA studies:

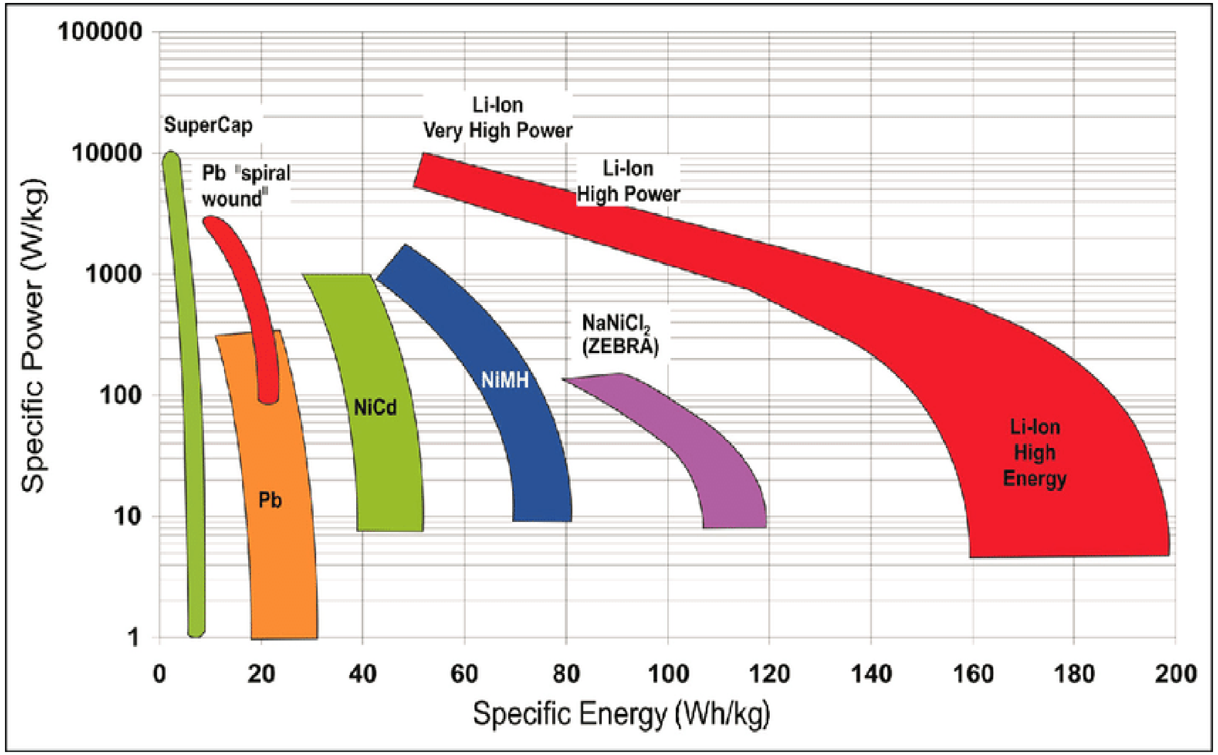
- Generic Space Qualification of 10F Nesscap Supercapacitors (ESA Contract No. 4000115278/15/NL/GLC/tk)
- Supercapacitors for launcher applications (ESA contract No. 4000119178/16/NL/PS)
- Graphene Enabled Supercapacitor Cell Optimization and Bank System Development (ESA No. 4000137745/22/NL/FE/mkn)
- Application of Supercapacitors on power system modules

Done

On-going

Not yet started

WHERE DO BATTERIES END AND SUPERCAPACITORS BEGIN?



The main difference between LIBs and SCs lies in the charge storage mechanism:

- LiBs involve redox reactions in the bulk of the active materials
- SCs operate through the accumulation of electrons at the surface of the electrode particles.

While clearly more electrons can be stored in the bulk, kinetics limitations arise from the slow diffusion of the ions.

LIBs operate in the electrochemical window where electrolyte is thermodynamically unstable.

Cycle stability:

- LiBs :> 5 000 deep cycles
- SCs: > 1 000 000 deep cycles

MAIN TRENDS IN THE 2000’s: FOCUS on HIGH-POWER PULSES NEEDS

SCs in Geostationary Earth Orbit subsystems:

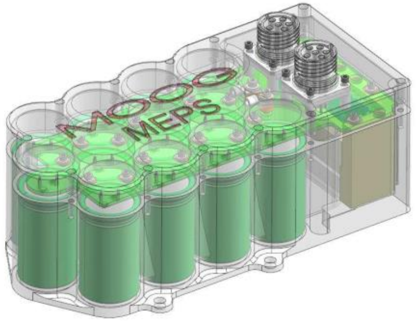
- to keep a satellite’s power supply from fluctuating as the satellite loads change, providing Power Bus voltage regulation (start of electrical propulsion thrusters, eclipse transitions…)
- to deploy for example the solar panels: power supply of the release mechanisms of the spacecraft

SCs in small-satellite earth-observation missions:

- to provide the necessary power and fulfil the low mass requirements for high-power radar

SCs in hybrid power supply subsystems in aerospace:

- flight control surface, vehicle actuation systems
- first prototypes of Modular Electric Power Systems (MEPS^{TM}) in aircrafts



SCs in electrical Thrust Vector Control of spacecrafts:

- to decrease the amount and duration of power loads on the batteries, and consequently extends the lifetime of the whole energy storage system
- to replace the cold gas (Xe, Kr) used generally to power supply a resistojet thruster

Use of SCs in launch vehicles:

- to optimize the power supply of pyrotechnics separation mechanisms during launch phase

Use of SCs in Mars exploration missions:

- to reduce the current heating needs for batteries, targeting ultra-low temperature SCs operating at - 70^{o}C

HIGH POWER BATTERY SUPERCAPACITOR SYSTEMS STUDY

- Inventory of relevant high-power applications in spacecraft and launchers
- High power energy storage technologies survey
- Impact on electrical power subsystem architectures of the use of hybrid systems (Batteries + SCs) and/or SCs
- Trade-offs with regard to the applications listed in the inventory

Main conclusions:

- The **high power characteristics of COTS SCs are not enough** to make the difference in order to ensure the power supply of the various electrical functions of a spacecraft and of launcher with an hybrid power system composed of COTS supercapacitors and secondary batteries has been performed

- **Spacecraft applications**: high-power LIDAR, radars and high-power actuators. For each application, it has been demonstrated that the use of 10 F supercapacitor cells in hybrid power systems could be a decisive advantage by contributing to the limitation of the main bus perturbations due to peak power

- **Launcher applications**: Electro-Mechanical Thrust Vector Control and pyrotechnics functions. Drastic gain in mass are expected by using 10 F to 100 F supercapacitor cells assembled in packs and used as single power source or combined with a battery pack to build a hybrid power system.

QUALIFICATION OF 10F COTS SUPERCAPACITORS (1/3)

PRELIMINARY STUDY

Inventory of 10 F COTS SCs components for space applications

Cap XX®
HS130 (2.4 F)

Maxwell®
PC10 (10 F)

Nesscap®
EHSR 0010C0-002R7 (10 F)

Maxwell®
BCAP0010 P270

Components assessment:

- SCs electrical test campaigns in Airbus D&S electrical laboratory
- SCs environmental test campaigns in EGGO: Fast temperature transients, vacuum exposure (short duration), vacuum exposure (long duration under voltage →similar degradation than ambient pressure), radiation, mechanical tests (vibration, shocks)
- SCs life tests

QUALIFICATION OF 10F COTS SUPERCAPACITORS (2/3)

Main conclusions of the preliminary study:

- COTS supercapacitors: interest and suitability for space applications.
- In particular, excellent performances of Nesscap® 10F 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.
- In 2015, Nesscap® has improved the sealing performance of the 10F part (ESHSR-0010C0-002R7UC – XP products family). This product is mass produced and commercially available since 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.
- In 2015, GSTP6.2 proposal initiated by Airbus D&S selected by ESA to qualify Nesscap 10F supercapacitor and associated BOSC

QUALIFICATION OF 10F COTS SUPERCAPACITORS (3/3)

- SCs qualification campaign (> 1500 Nesscap® 10F)
- BOSC qualification campaign

Main conclusions:

SCs qualification campaign

- Supercapacitor is a product which fills the gap between batteries and capacitors. Its electric performances in power peak make it possible to optimize our functions of distribution and order. The very good behaviour with cycling makes it possible to meet the needs for mission of long life
- Its major drawback is, as for the battery, a calendar deterministic ageing which depends on the temperature and the charging voltage. It is manageable by applying derating in voltage and limiting the use temperature to 40° C.
- Nesscap 10F at component and BOSC are ready for flight
- The TRL is at 6 level and entry in ESA EPPL Part II
- R&T activities necessary to improve power density and high temperature lifetime

BOSC qualification campaign

- BOSC based on this supercapacitor has been space qualified

OVERVIEW OF RESEARCH AND DEVELOPMENT OF NEW MATERIALS (1/3)

- Activity: GRAphene enabled supercapacitor Cell (GRACE)
- Contractor: Pleione (Greece)
- Objective of the activity: to select, manufacture, test and benchmark graphene-based supercapacitor electrodes by testing different graphene commercially available products in different compositions, as well as establishing a supercapacitor cell manufacturing process with all the necessary Quality Assurance and Product Assurance measures.

Main conclusions:

- **Promising results at electrode level**, with specific capacitances of 323 F/g and 356 F/g (activated carbon electrodes120 F/g).
- **SC pouch cells,** transfer ratio of the electrode property around of the order of magnitude of 45% (SC maximum capacitance value of 37 F instead of 80F expected).
- The **targeted value of energy density was achieved** (around 30 Wh /kg, so higher than 10 Wh/kg).
- Upon the completion of the de-risk GRACE activity the TRL of technology was 4.

Axis of improvement:

The **life cycle of the cells was lower than expected**. A more comprehensive study shall be performed on the combination and suitable pairing of electrolyte/electrode system. (Graphene Enabled Supercapacitor Cell Optimization and Bank System Development (ESA No. 4000137745/22/NL/FE/mkn)

OVERVIEW OF RESEARCH AND DEVELOPMENT OF NEW MATERIALS(2/3)

- Activity: Carbide-derived carbon – SPACECAP supercapacitors
- Contractor: Skeleton Technologies (Estonia)
- Objective of the activity: to select, manufacture, test and benchmark CDC-based supercapacitor electrodes by testing different CDC materials, as well as establishing a supercapacitor cell manufacturing process with all the necessary Quality Assurance and Product Assurance measures.

Main conclusions:

- **63 SpaceCap supercapacitor cells (100F) were submitted to a set of tests,** taking as a reference the F4 chart of the draft ESCC Generic Specification "Supercapacitors, EDLCSC pouch cells",
- **Relatively large variance in electrical performance**: around 20% for capacitance, and 25% for Equivalent Serie Resistance (ESR), and **high variance in life test performance and life test failures**: 2 out of 15 cells failed the voltage hold tests, 3 out of 6 cells did not pass the life cycle test. The ones that passed the test showed a variance of the order of magnitude of 40%.

Axis of improvement:

Need to improve the stability of the electrical performances during life test, by studies at electrode material and electrolyte level

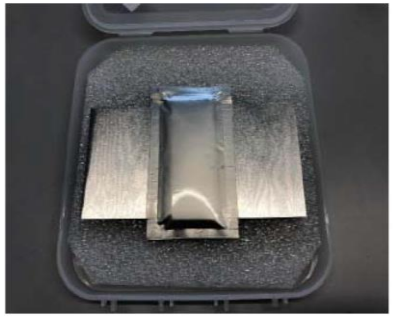
OVERVIEW OF RESEARCH AND DEVELOPMENT OF NEW MATERIALS(3/3)

- Activity: Vertically Aligned Carbon Nanotubes based supercapacitors for launchers
- SCs manufacturer: Nawatechnologies
- Objective of the activity: to develop high-energy supercapacitors (15 Wh/kg) in order to power supply, the pyrotechnics functions of the launchers, and to design a Bank of Supercapacitors (BOSC)

Main conclusions:

- Capacitance of the cells of the order of magnitude of 60F, versus the 200F required, enery density of 4.80 Wh/kg
- Lack of electrical performances at the temperature of -30° C,
- Poor behaviour of the cells assembled in BOSC under vacuum conditions.

Upon the completion of the activity the TRL of technology was 4.

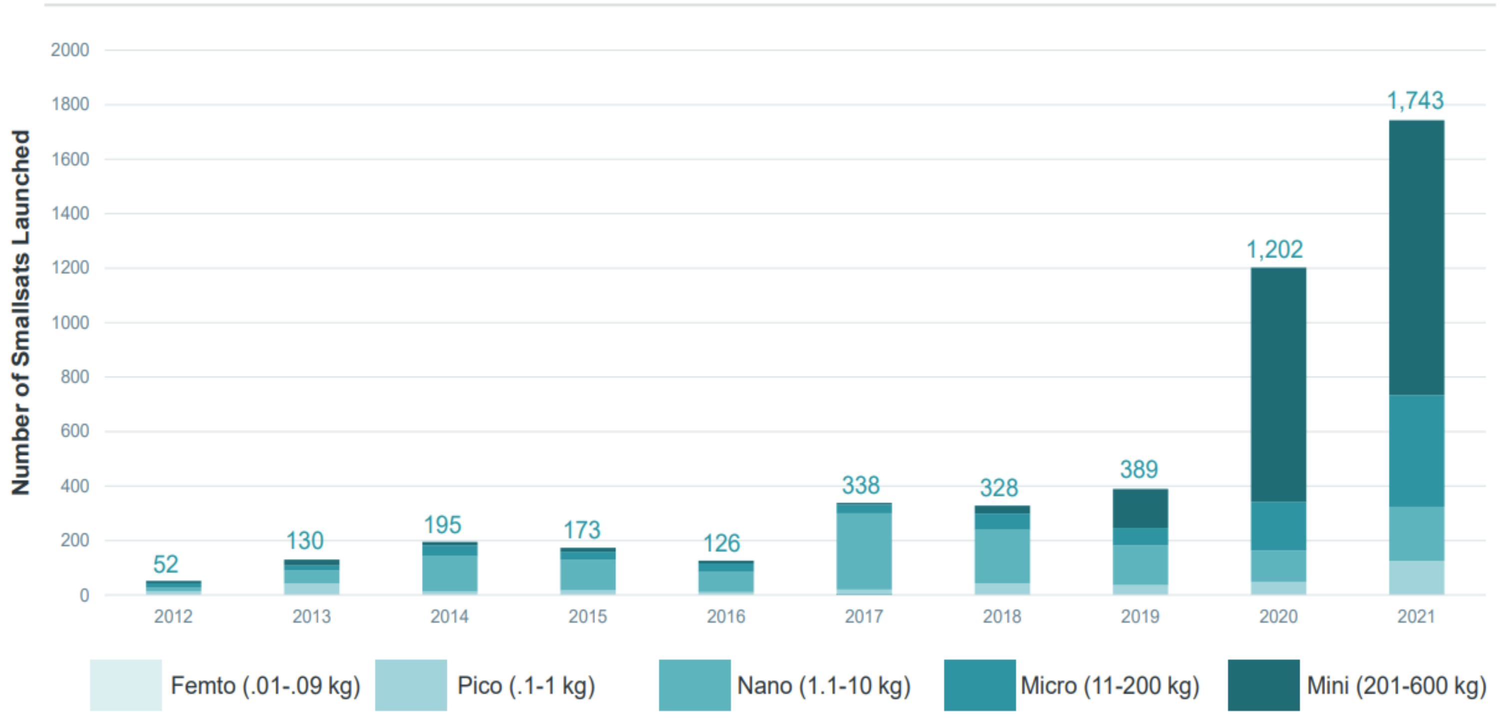


Axis of improvement:

- At material level: a more comprehensive study shall be performed on the combination and suitable pairing of electrolyte/electrode system
- AT SC level: improvements of the pouch cell packaging are required to sustain vacuum environment

SUPERCAPACITORS FOR SPACE APPLICATIONS: OPPORTUNITIES (1/3)

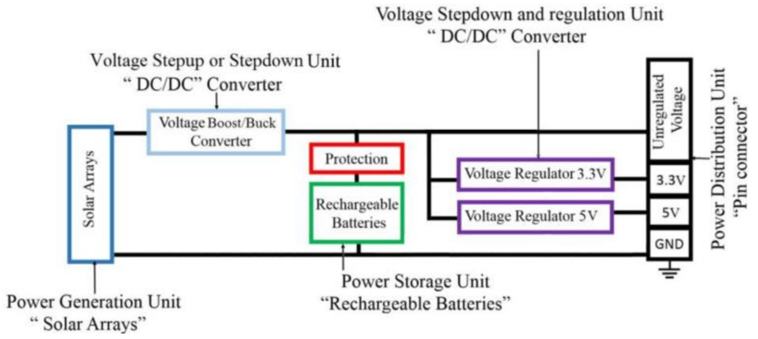
- Growth market of the small spacecrafts, weighting between 100 kg and 200 kg
- Constraints in the allowable on-board battery volume => impact on the maximum power supply capability (limited in ranges between 70 W to 200 W)
- Need to enhance these satellites’ power performance
- New opportunities appear for the use of supercapacitors in space: high power capabilities, hybrid power supply, EPS, IoD

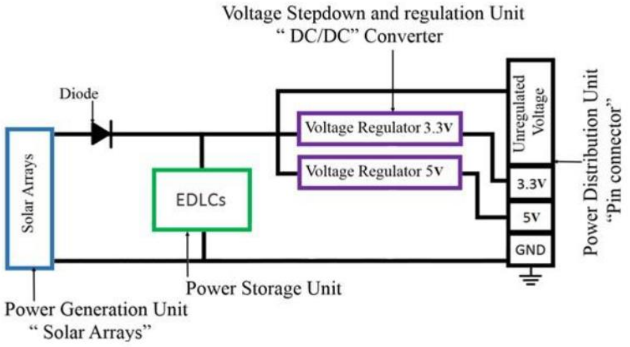


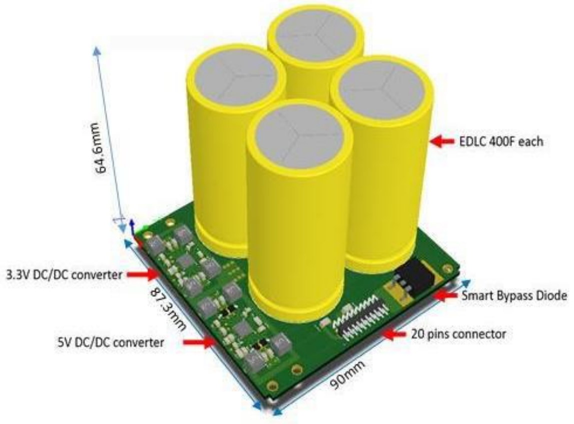
SUPERCAPACITORS FOR SPACE APPLICATIONS: OPPORTUNITIES (2/3)

1U CubeSat Electrical Power System

Energy storage System for the Payload Onboard the CSUNSat1 CubeSat







Main achievements:

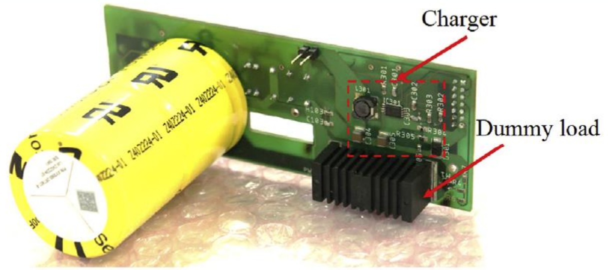
- EDLC-based EPS board developed and tested in space environments, the total EDLC capacitance was 1600 F (Eaton 400-F EDLC)
- CubeSat power consumption profile was assumed to be from 920 mW to 2.67 W
- Electrical Power System occupying a volume of 90 mm × 87.3 mm × 64.6 mm.
- Functionality of the board was tested, assuming realistic power, voltage, and current profiles based on actual orbital periods, and assuming release of the satellite from the International Space Station (ISS).
- Board was proven to withstand space environments, and to provide the power to operate a CubeSat in orbit, with a remaining energy level of 52% at the end of eclipse

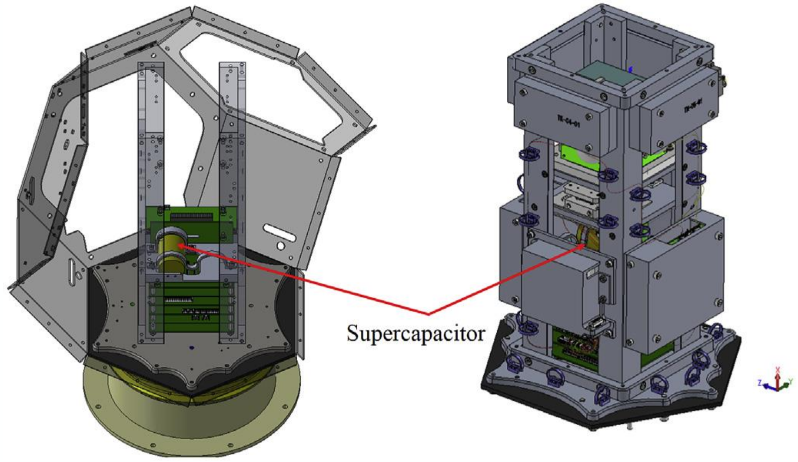
Source: Kim, S. et al., Design, Fabrication, and Testing of an Electrical Double-Layer Capacitor-Based 1U CubeSat Electrical Power System Journal of Small Satellites, Vol. 7, No. 1, pp. 701–717, 2018.

SUPERCAPACITORS FOR SPACE APPLICATIONS: OPPORTUNITIES (3/3)

In-orbit demonstration of COTS supercapacitors

Energy storage System to power supply one of the payloads of the spacecraft Ten-Koh





Main achievements:

- Ten-Koh was launched on-board H-IIA F40 on 29 Oct 2018 and remained operational until mid-March 2019
- Discharge power of as much as 6.87 W has been demonstrated in-orbit
- Only a − 0.4 to − 2.4% change of capacitance between the in-orbit and on-ground cycles has been observed
- Self-discharge over two days in orbit has been calculated as less than 2.5%
- The SC was charged and discharged three times in-orbit and survived over 2000 orbits in LEO (141 days until the spacecraft became unresponsive, with orbital period of approx. 5797 s)

Source: J. Gonzalez-Llorente, A. A. Lidtke, K. Hatanaka, L. Limam, I. Fajardo, K.I. Okuyama, In-orbit feasibility demonstration of supercapacitors for space applications, Acta Astronautica 174, 294-305, 2020.

CONCLUSIONS AND OUTLOOKS

The studies reported have demonstrated the successful use of supercapacitors, in the power supply and/or the hybrid power supply of several classical spacecrafts' applications (high-power LIDAR, radars and high-power actuators) and of two functions of launchers (pyrotechnics and EMTVC).

The studies have shown the limitations and constraints related to the use of COTS supercapacitors for spacecrafts.

Enhancement of the performances of existing supercapacitors is an innovative field where new materials (graphene,…) are going to play a determinant role in order to develop high-energy supercapacitors (> 15 Wh/kg) and hybrid supercapacitors (e.g Lithium Carbon capacitors with 50 Wh/kg energy density).

With the proliferation of small satellites in recent years, the use of COTS supercapacitors that have not been developed for space applications is of interest to the space community.

In the future, innovative supercapacitors based on graphene could be an enabler for the small satellites market, enabling to propose improved and/or new services and extended life duration

Thank you for your attention
Any questions?

If you have any questions or you want to know more about the topic you are welcome to contact me:

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