Technologies and applications of Supercapacitors

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University of Mondragon, June 22th 2012

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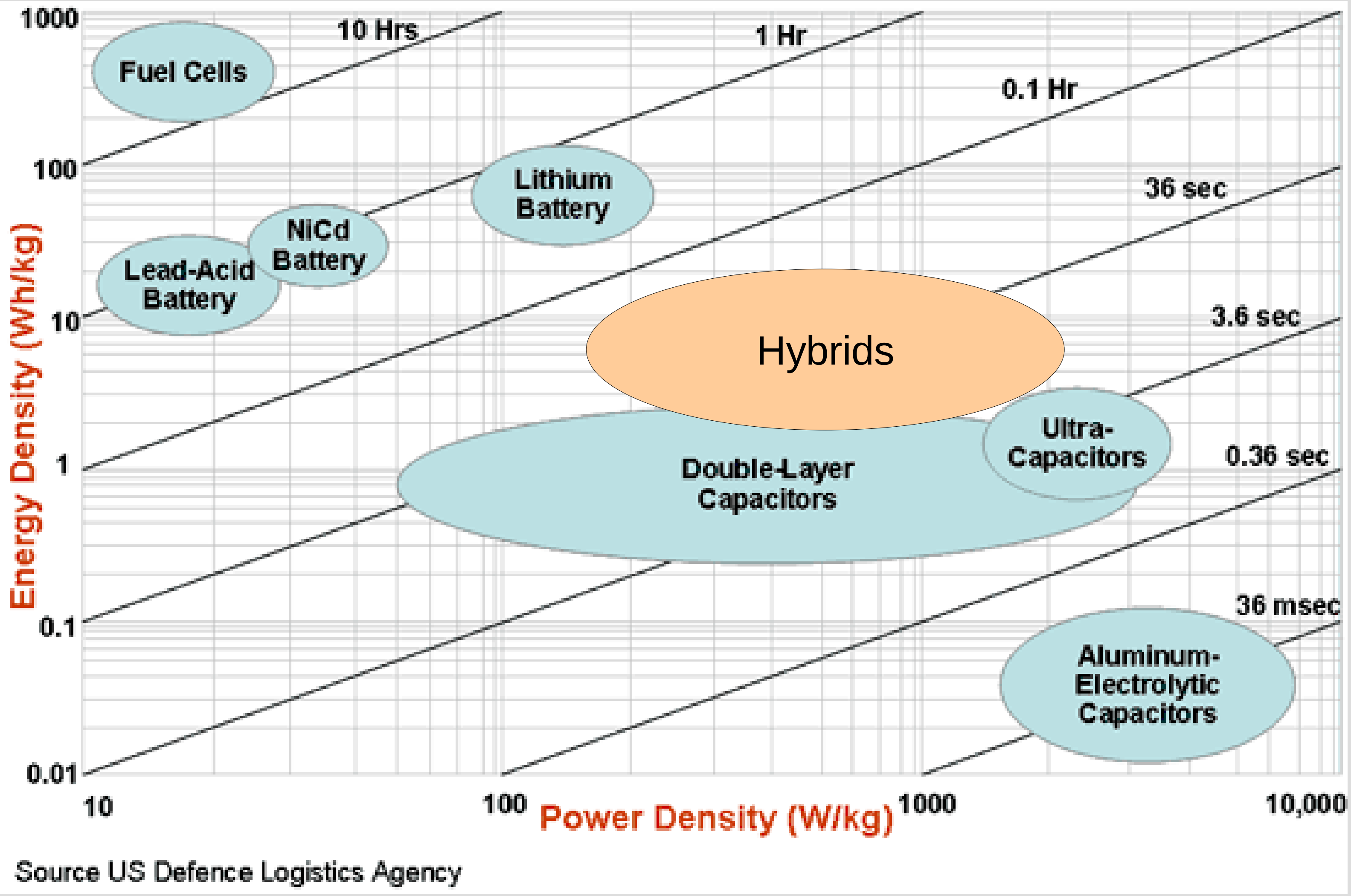
Supercapacitor technologies

- Construction
- Asymmetric or Hybrid type
- Properties

Ragone plot



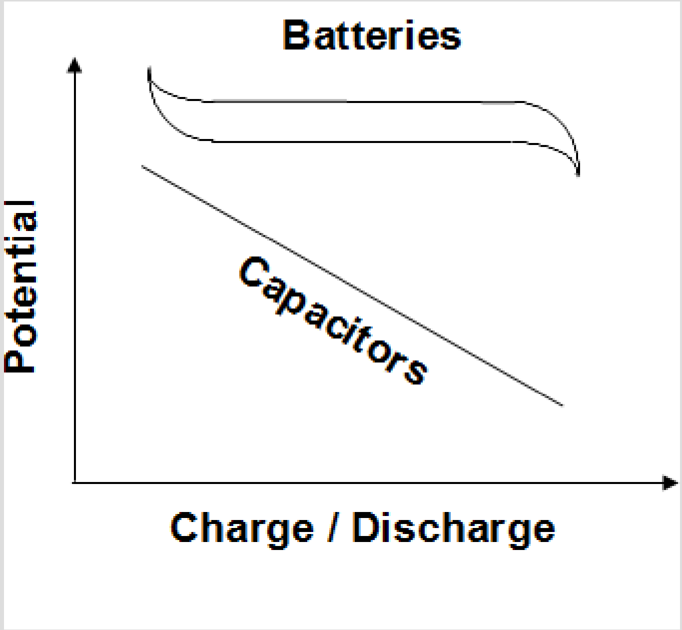
1000
100
10
1
0.1
0.01
10 Hrs
1 Hr
0.1 Hr
36 sec
3.6 sec
0.36 sec
36 msec
Fuel Cells
Lithium Battery
NiCd Battery
Lead-Acid Battery
Hybrids
Ultra-Capacitors
Double-Layer Capacitors
Aluminum-Electrolytic Capacitors
Energy Density (Wh/kg)
10
100
Power Density (W/kg)
1000
10,000
Source US Defence Logistics Agency

Electrochemical **Energy storage mechanisms**

Battery

Pb, NiCd, NiMH	Faradaic, Redox
Li^+…	Faradaic, Intercalation
Pseudocapacitor	Faradaic, Intercalation
Double layer (ECDL)	Electrostatic

Electrochemical Capacitor



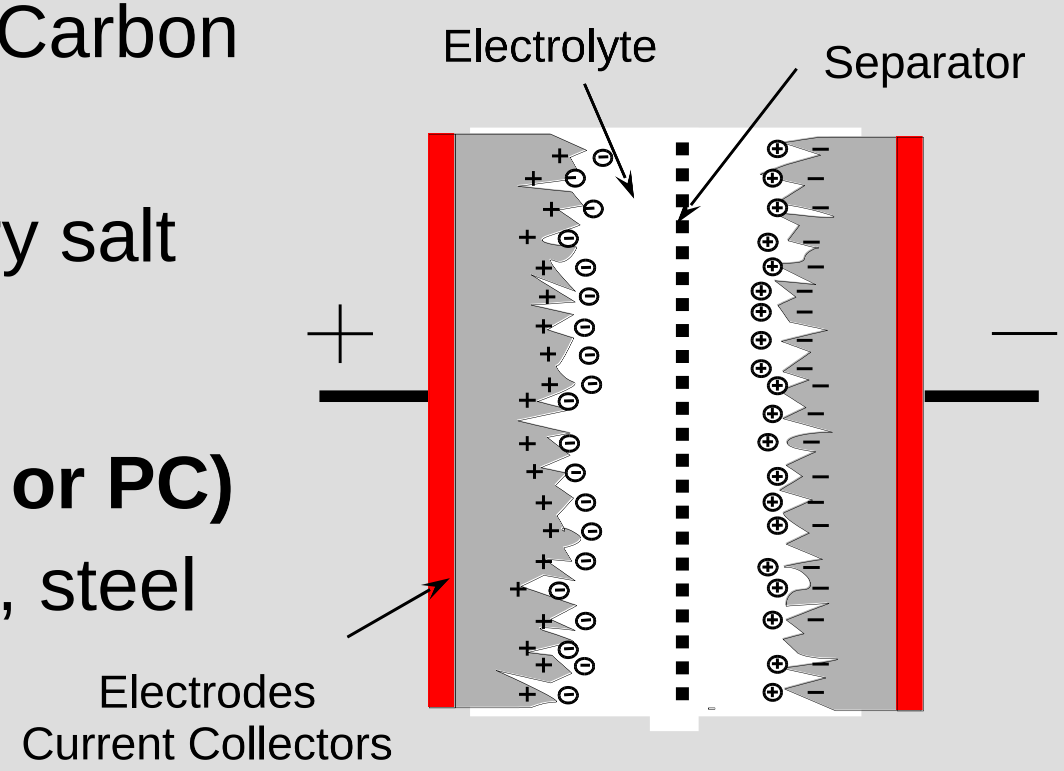
- **Faradaic charge transfer** (Redox)
  - $U = Q\,\Delta V$
  - $\Delta V = Cste$
  - Irreversible cycling
- **Electrostatic**
  - $U = 1/2\,C\,V^2$
  - $V = Q / C$
  - Reversible cycling

- No absolute limits between batteries & capacitors
- Intercalation = mechanical expansion = aging

Ultracapacitor composition

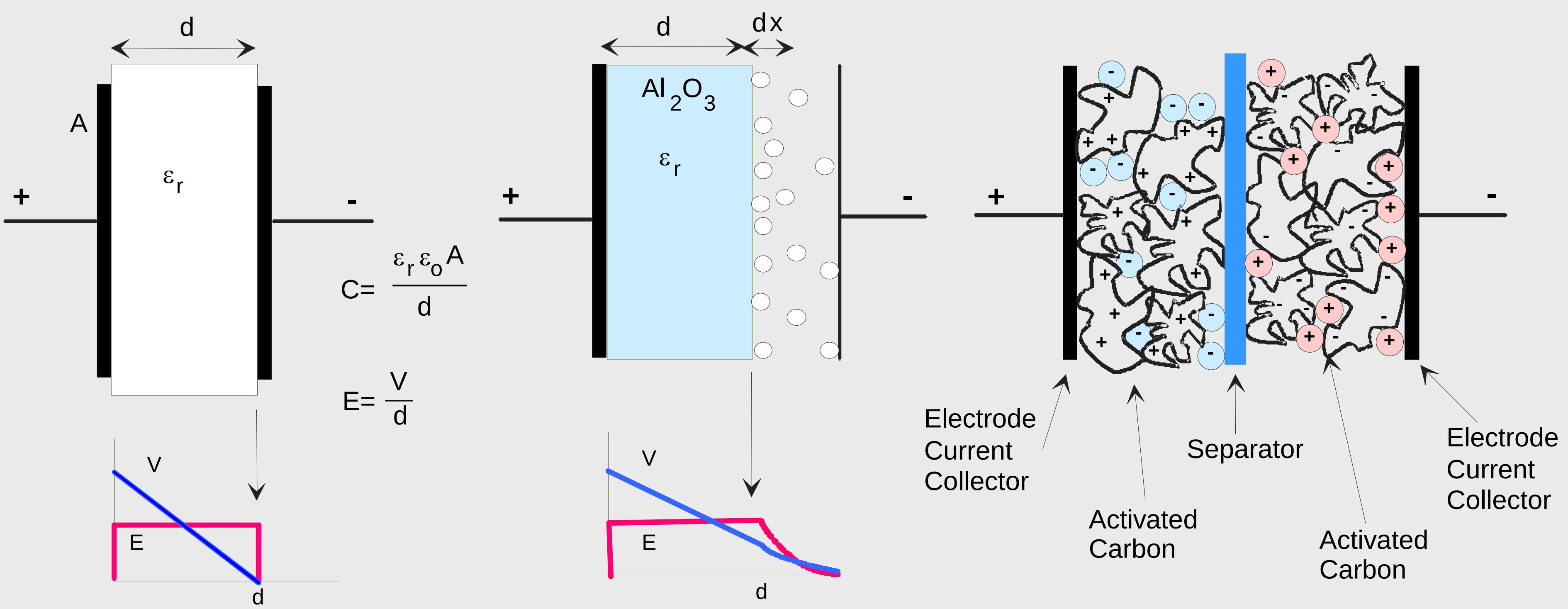
Ultracapacitors are composed of the following major components:

- Electrodes: Activated Carbon
- Separator: Cellulose
- Electrolyte: Quaternary salt (tetraethylammonium tetraflouroborate)
- **Organic solvent (AN or PC)**
- Other: Aluminum, steel

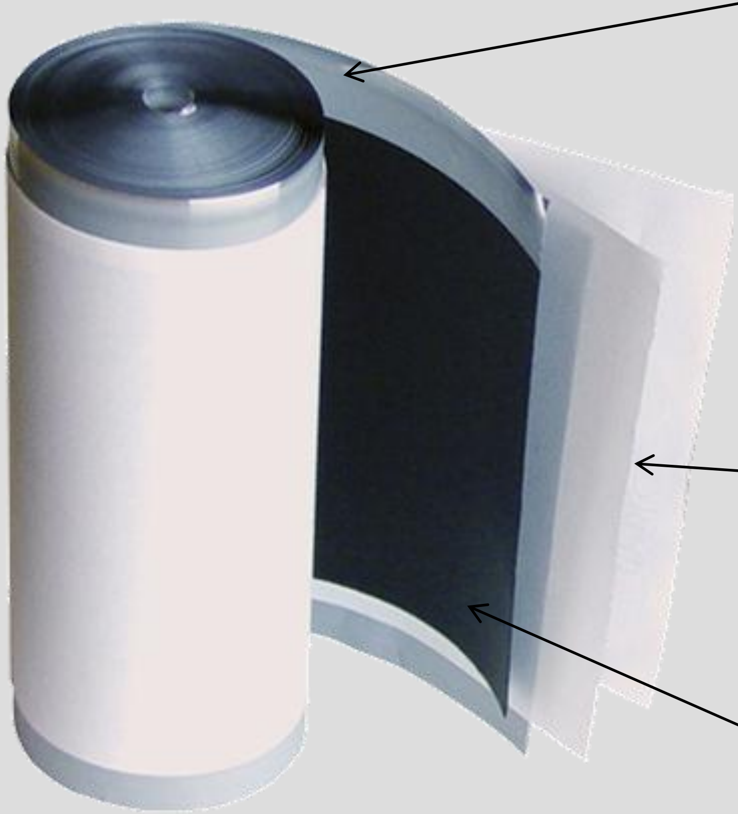


Capacitor Technologies

Electrostatic **Electrolytic** **Electrochemical double-layer**



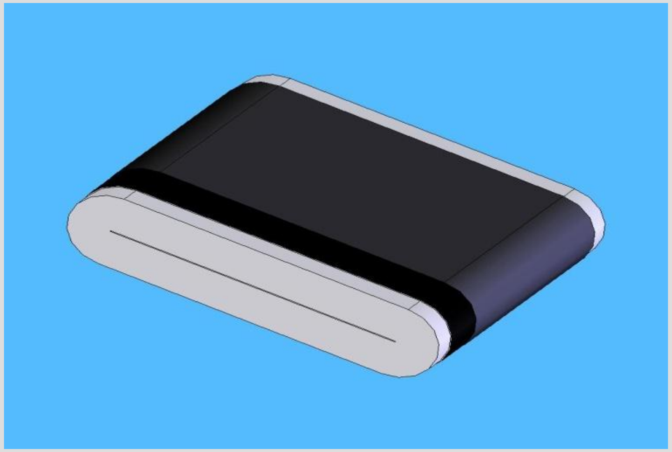
Supercapacitor winding



Aluminum collector extension

Separator

Carbon coating



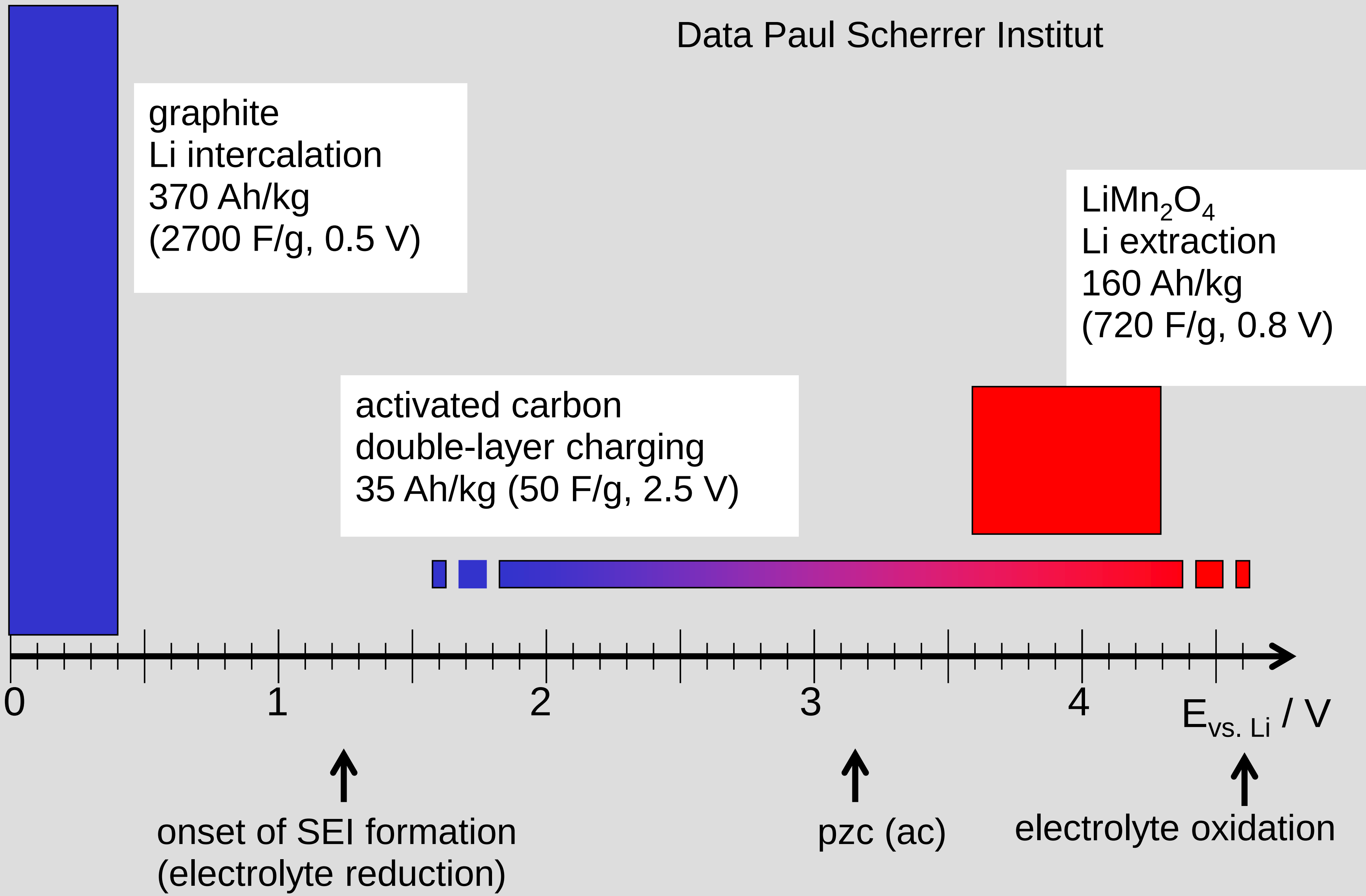
Hybrid supercapacitors

- Hybrid structure which have been considered
- Carbon (Electrochemical) – Electrolytic capacitor
- Carbon (Electrochemical) – Li Battery anode
- Li Battery cathode – Carbon (Electrochemical)

- The battery electrode works at constant potential
- The ECDL electrode is polarized with the voltage

Hybrid supercapacitor

Data Paul Scherrer Institut

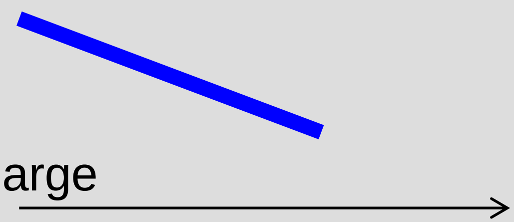


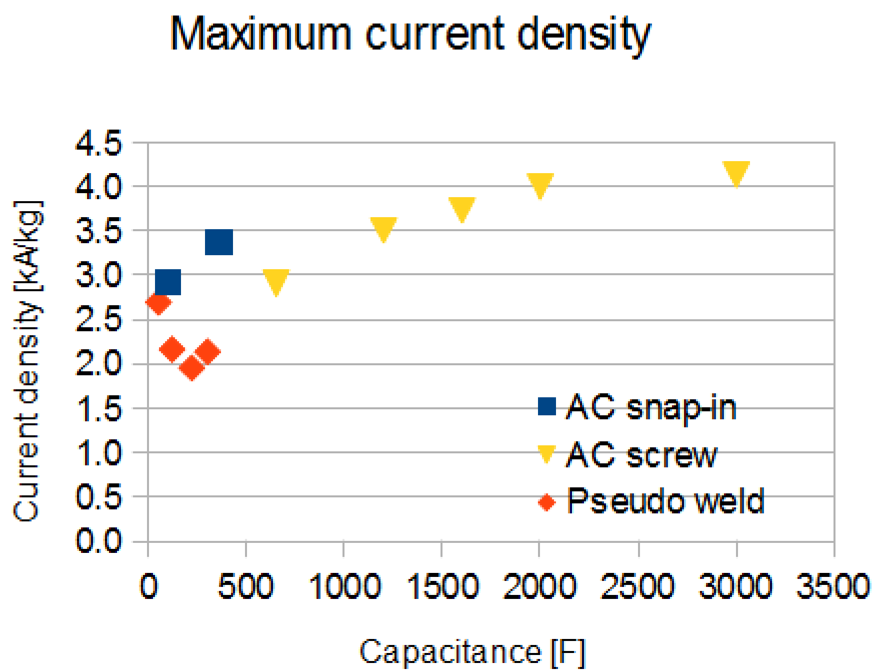
Nesscap EDLC / hybrid

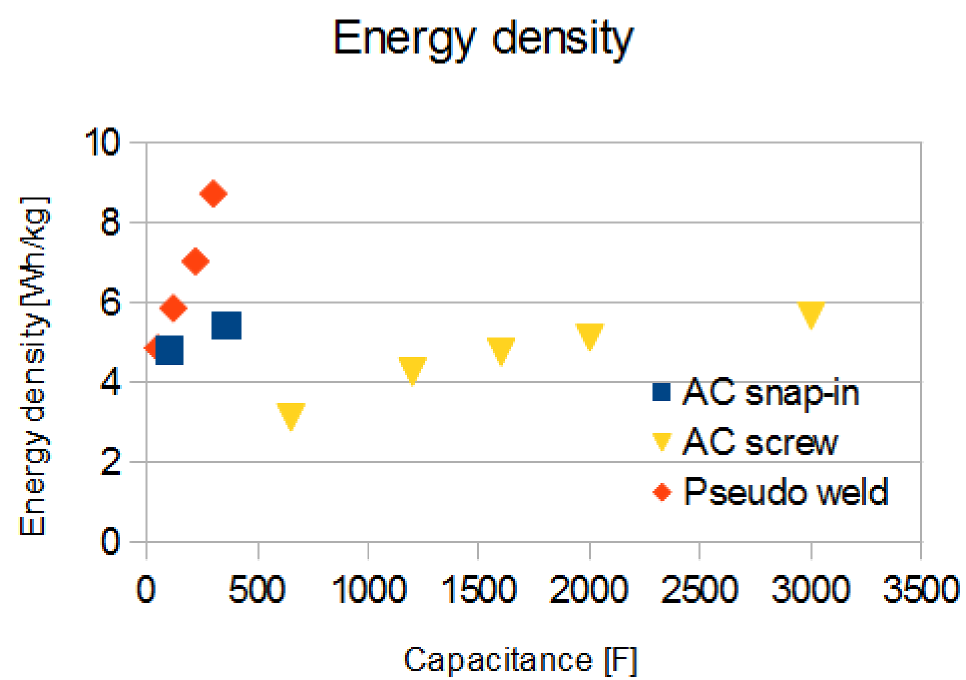
Positive: $LiCoO_2$ or $LiMn_2O_4$

Negative: AC

Voltage: min 0.9 V to max 2.3 V



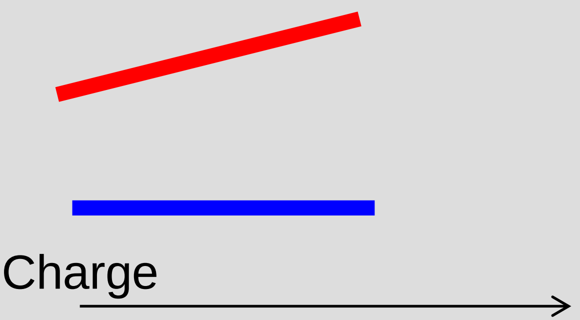




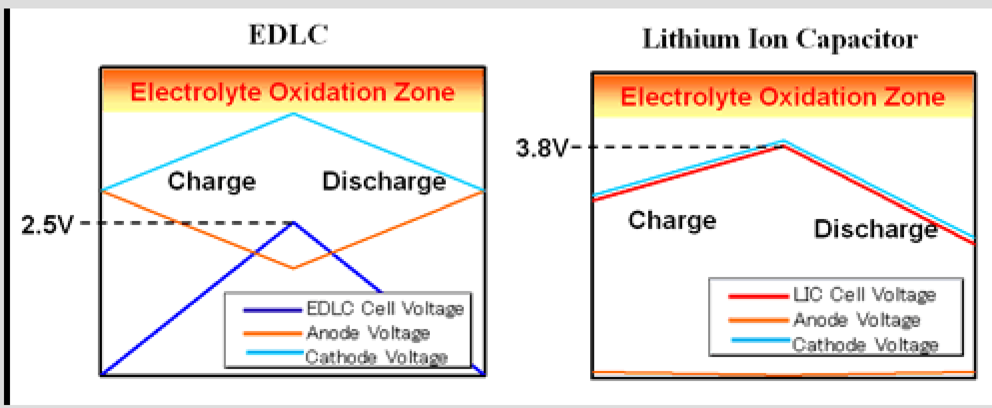
Lithium ion capacitor (LIC)

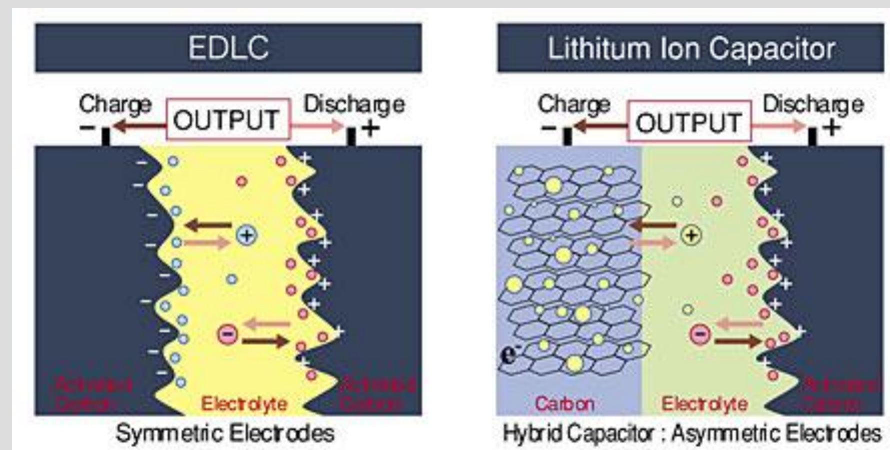
Positive: AC

Negative: Graphite or carbon nanofiber pre doped with $Li_4Ti_5O_{12}$



Voltage: min 2.2 V to max 3.8 V





http://www.jmenergy.co.jp/en/product.html

Tauyo Yuden LIC2540R 3R8207: 2.2 to 3.8 Vdc, C = 200 F, Rs = 50 mΩ, **τ = 10 s**

http://www.t-yuden.com/news/detail.aspx?id=166

Capacitance and ESR: f and T

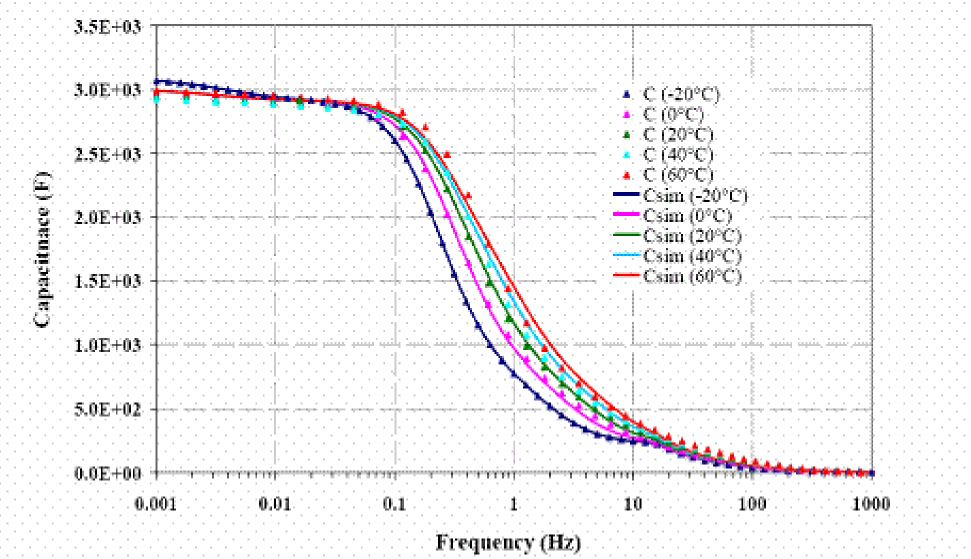


Figure 1: BCAP0010 capacitance frequency spectrum for 5 different temperatures.

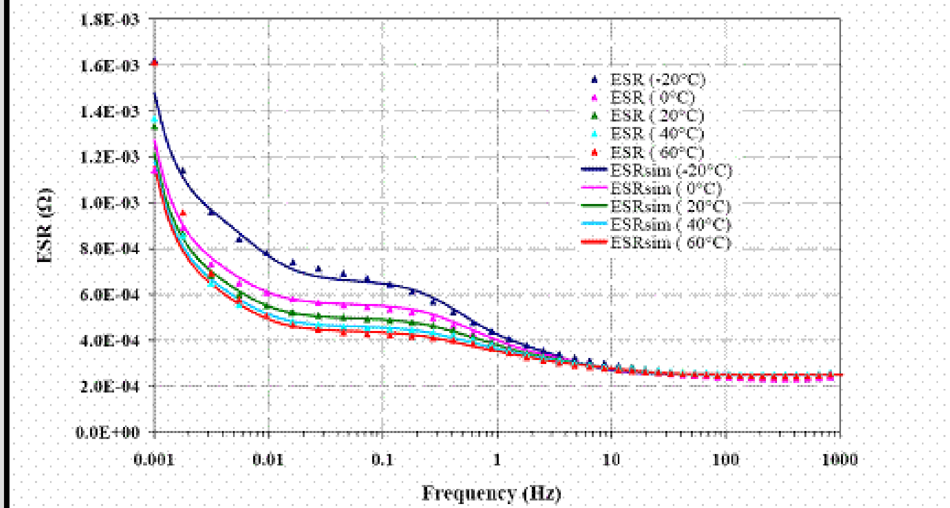
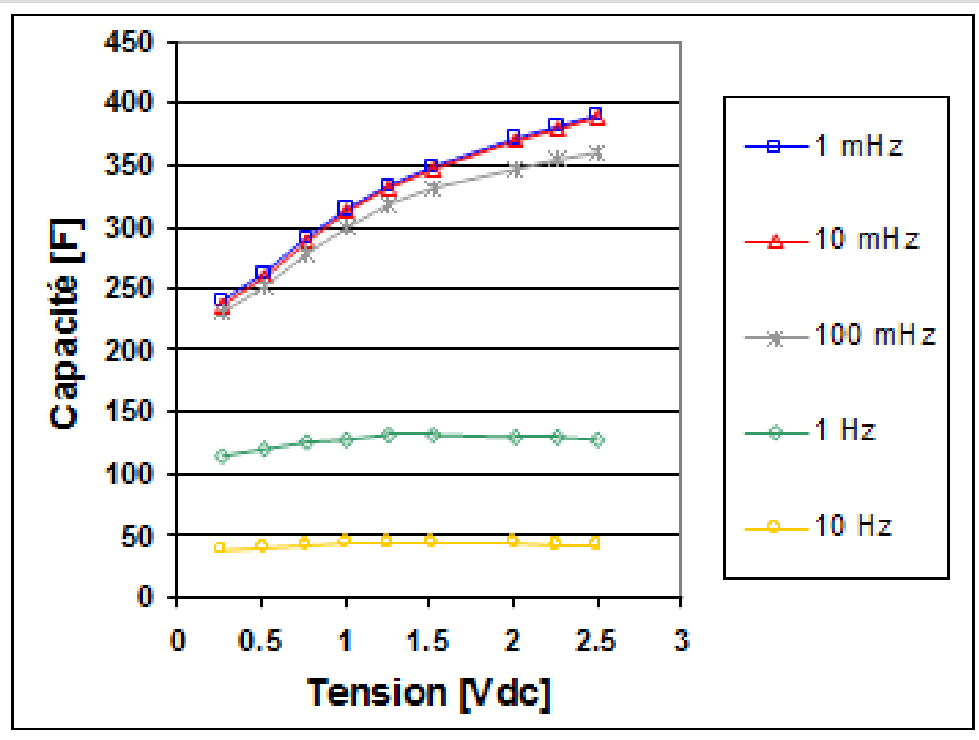
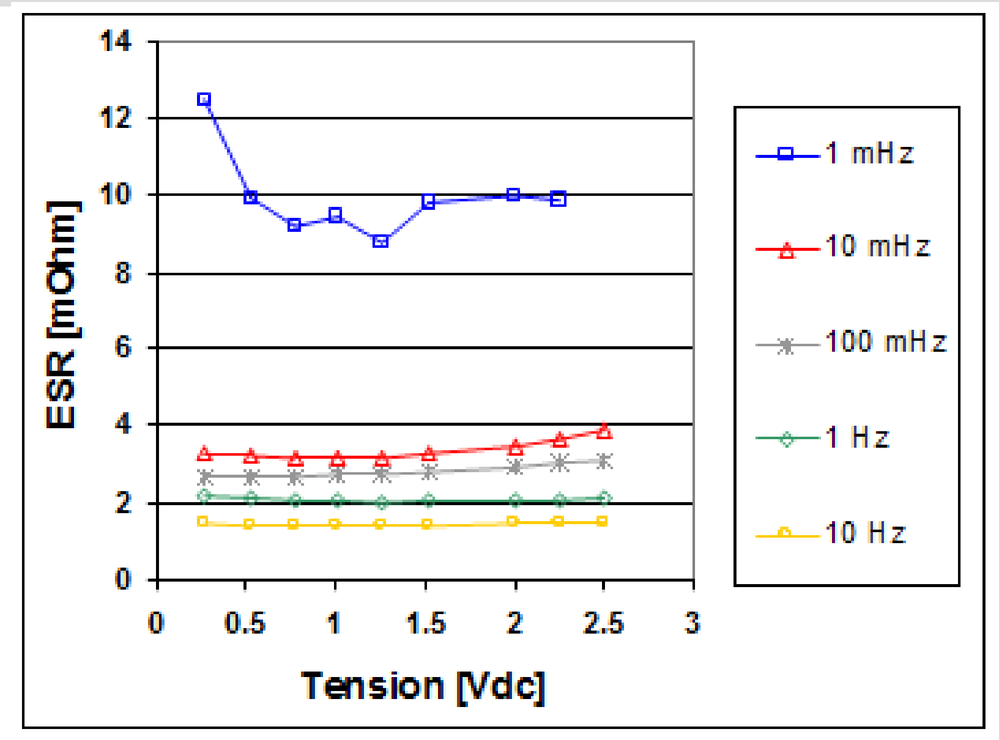


Figure 2: BCAP0010 Series resistance frequency spectrum for 5 different temperatures.

Capacitance and ESR: f and U

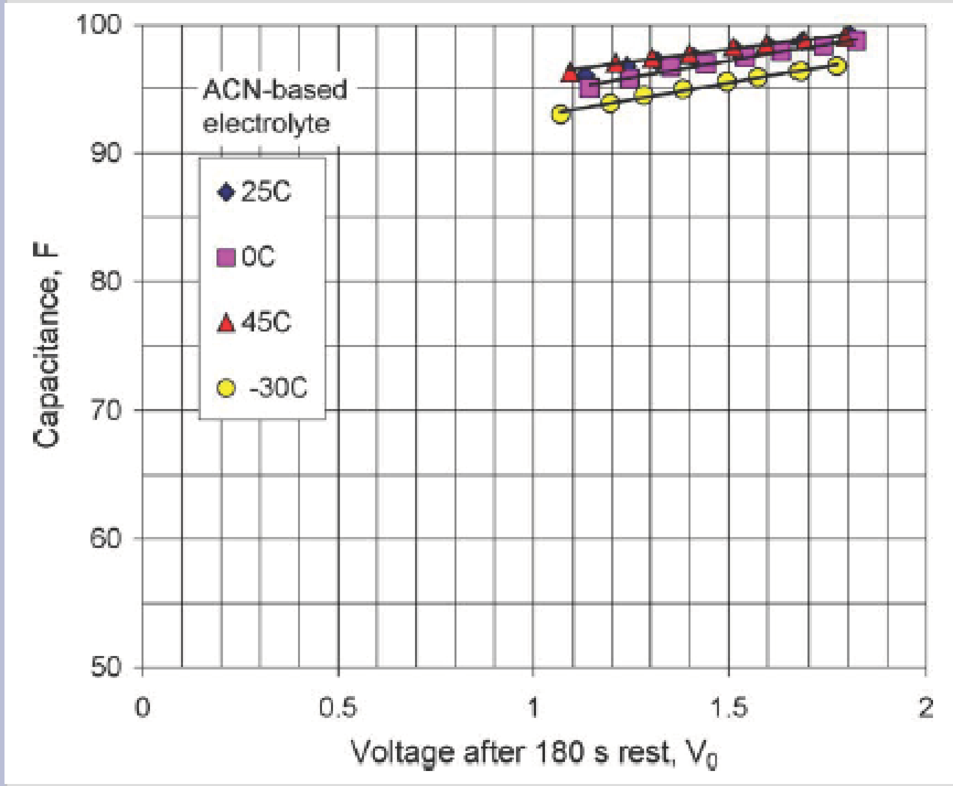




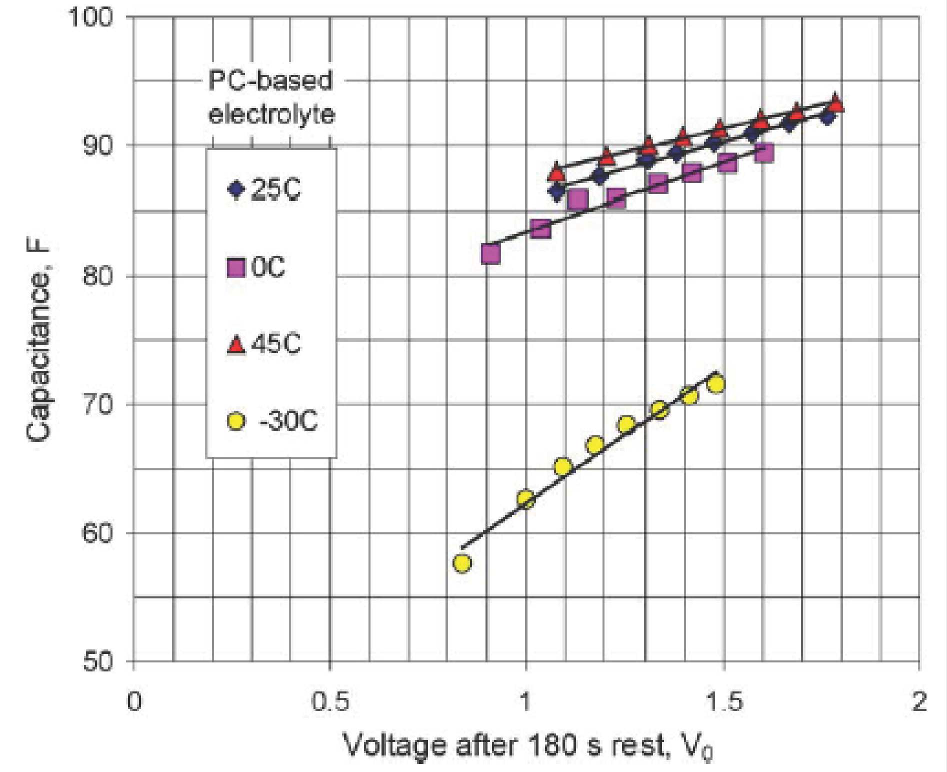
- Maxwell 350 F ultracapacitor

Capacitance for different solvants

Acetonitrile



Propylene carbonate

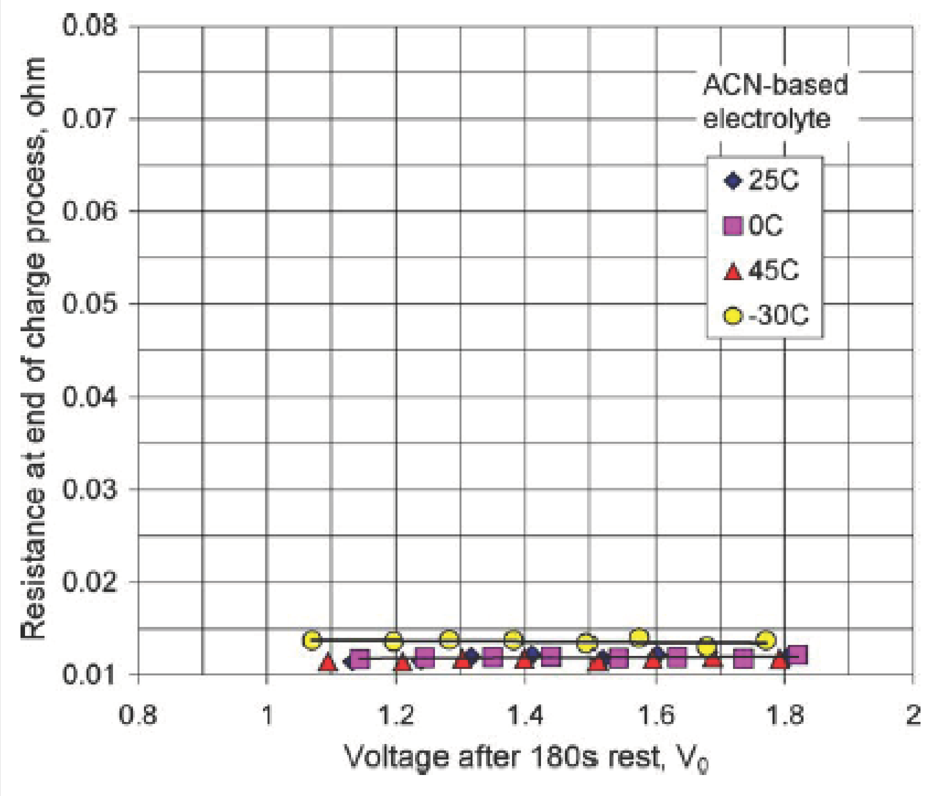


Smaller capacitance variation in acetonitrile (Function of T & U)

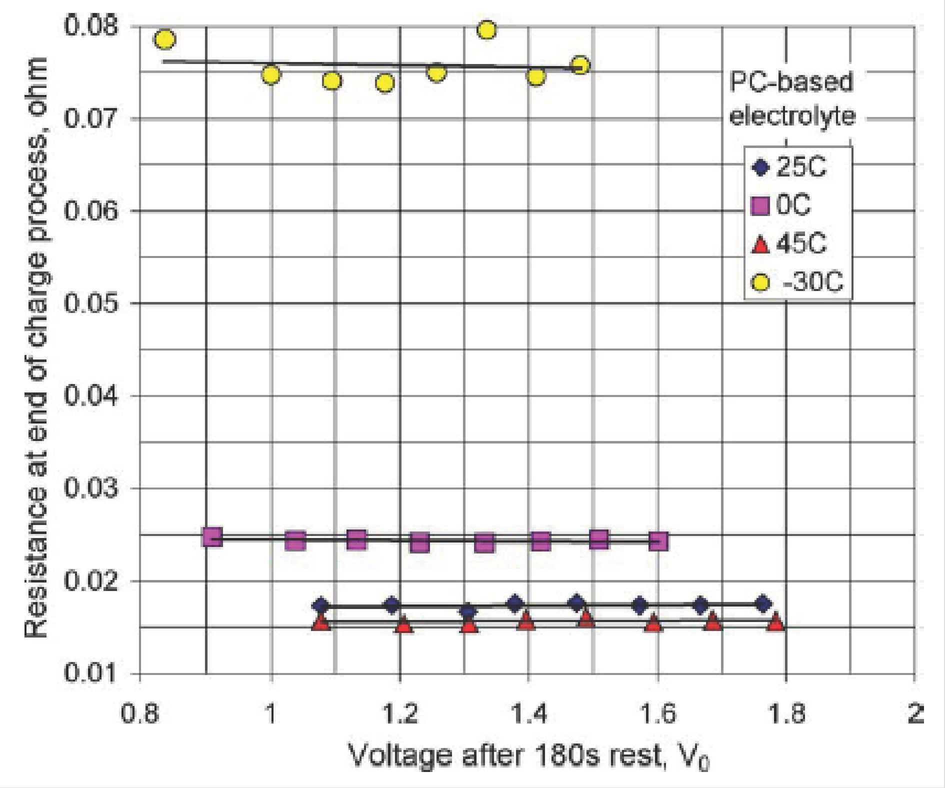
- Ping Liu, Mark Verbrugge, Souren Soukiazian, Journal of Power Sources 156 (2006) 712–718

Series resistance for different solvants

Acetonitrile



Propylene carbonate



Series resistance much smaller in acetonitrile

- Ping Liu, Mark Verbrugge, Souren Soukiazian, Journal of Power Sources 156 (2006) 712–718

Self-discharge - Leakage current

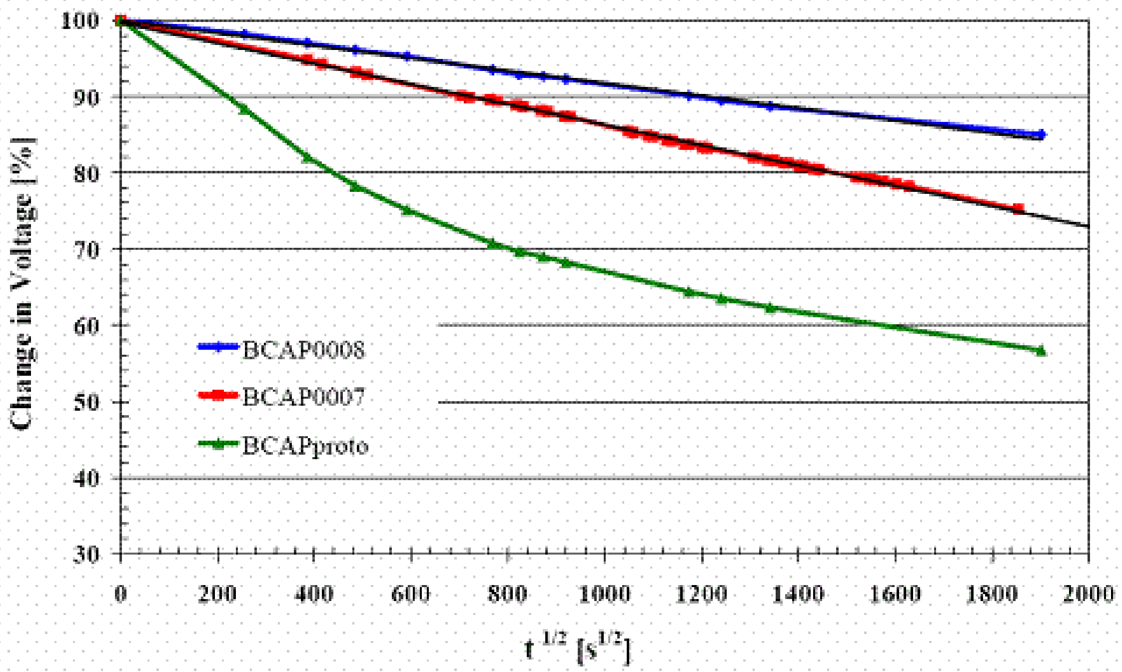


Figure 2: Supercapacitors selfdischarge controlled by diffusion show a linear voltage fading in square root plot.

- montena ultracapacitors

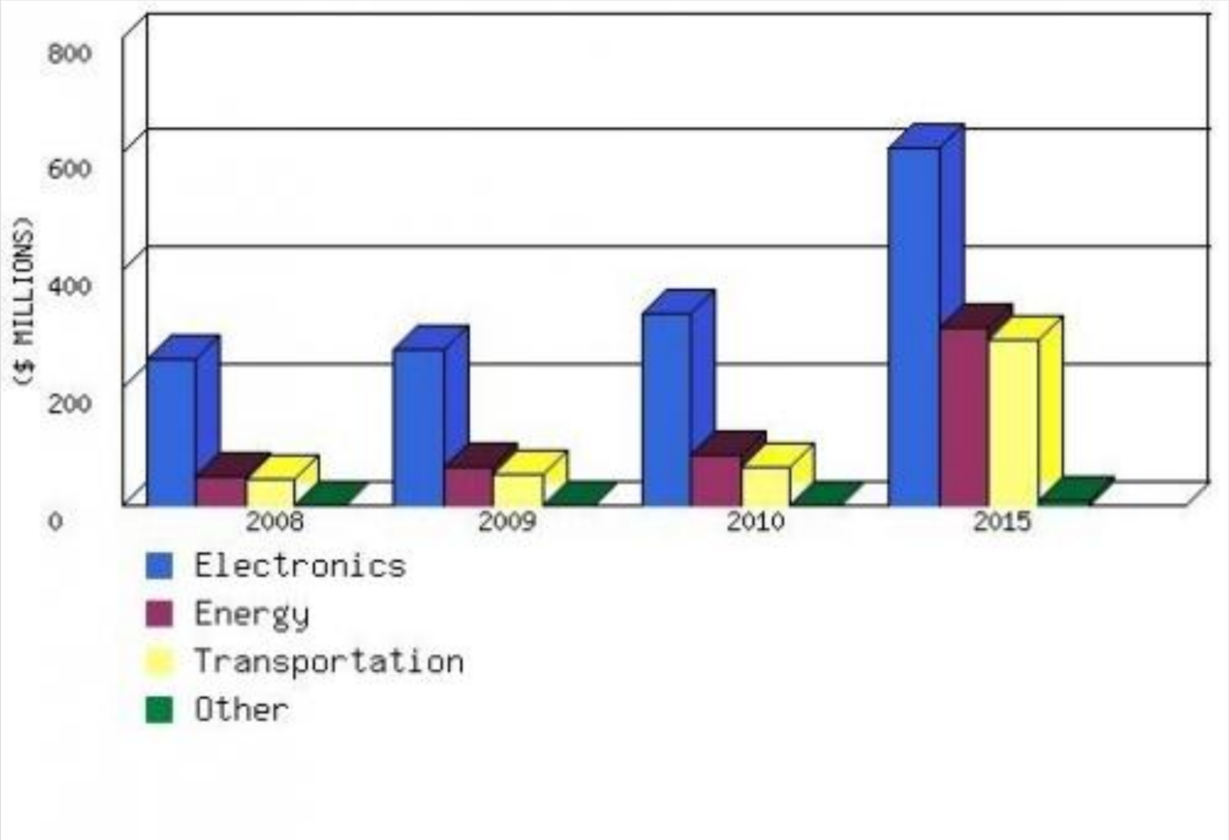
Ultracapacitor market

Ultracapacitor market estimations

- Sept 2006: iRAP estimates that the $272 million worldwide ultracapacitor business in 2006 will continue to grow at an average annual growth rate of 15.3%, to reach **$560** million in **2011**.
- June 2009: Lux Research finds the capacitor-based storage market can be expected to reach $877 million by 2014, up from $208 million in 2008.
- November 2010: NanoMarkets reports that worldwide sales of supercapacitors (EDLCs) will grow from around **$400** million in **2010** to reach about $3.0 billion by 2016
- January 2011: BCC research reports that the global market for supercapacitors is estimated at **$470** million in **2010**. Demand for supercapacitors is projected to continue growing at a rate during the next 5 years, reaching a value of $1.2 billion in 2015, a compound annual growth rate (CAGR) of 20.6%.

- 2010 November Nanomarkets
  - Sees the fastest growing market for supercapacitors in the **consumer electronics** industry, which is expected to demand more than $725 million in these devices by 2016.
  - believes that frequency regulation in next-generation electricity grids will provide $540 million in business for supercapacitor firms in 2016.
  - The transportation/vehicular sector’s market share, which currently accounts for almost 60% of the supercapacitor market, will fall to around 35% as new applications for supercapacitors emerge, according to the report.

GLOBAL MARKET FOR SUPERCAPACITORS, 2008-2015



- BCC Research, January 2011

Ultracapacitor applications

Automated Meter Readers (AMR)

- It’s a remote monitoring system for electricity meters
- Energy storage sub-system for power management
- Replacement of Lithium Ion or conventional batteries by ultracapacitors

Benefits

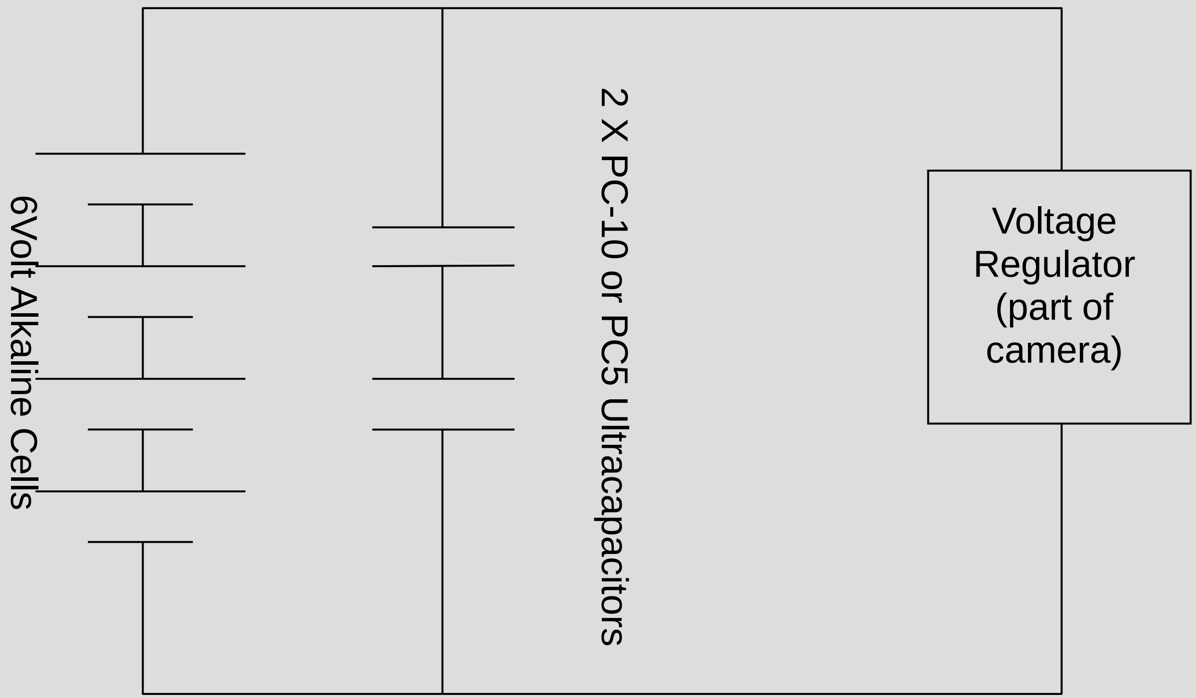
- 100% increase of lifetime by using ultracapacitors instead of Lithium Ion
- 300% increase of lifetime by using ultracapacitors instead of conventional batteries
- Simpler design-in process of the six PC10s in each unit as they are mounted flat on the board
- Lighter and smaller

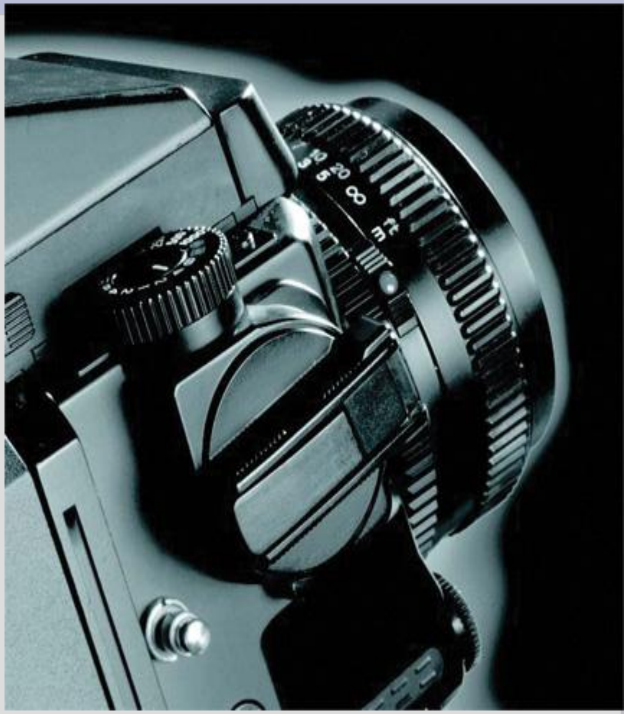
Elster’s
A3 Alpha® meter

Consumer electronic: Cutting Tool

- Cordless power copper tubing cutter
- Uses PC10 for peak power, in parallel to a battery
- Benefits: Reduced cutting time by 50%

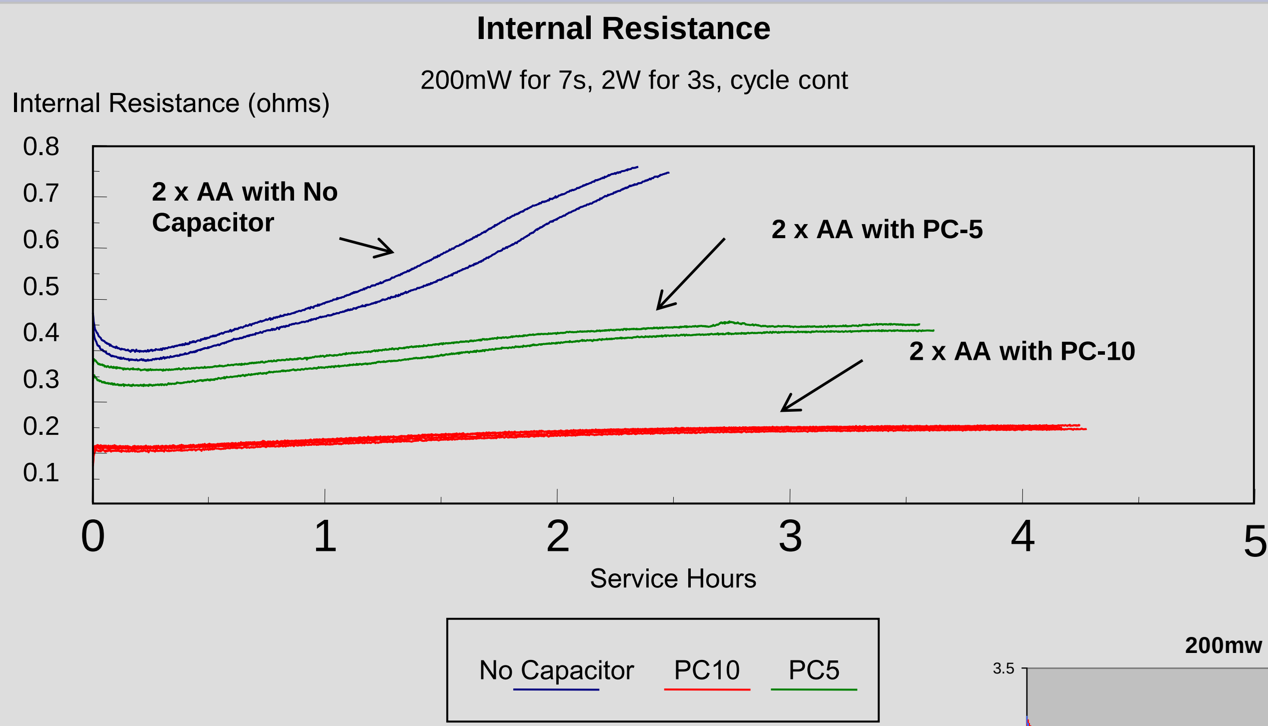
Consumer electronic: Digital Cameras

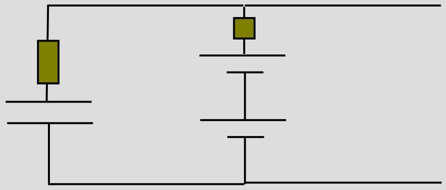


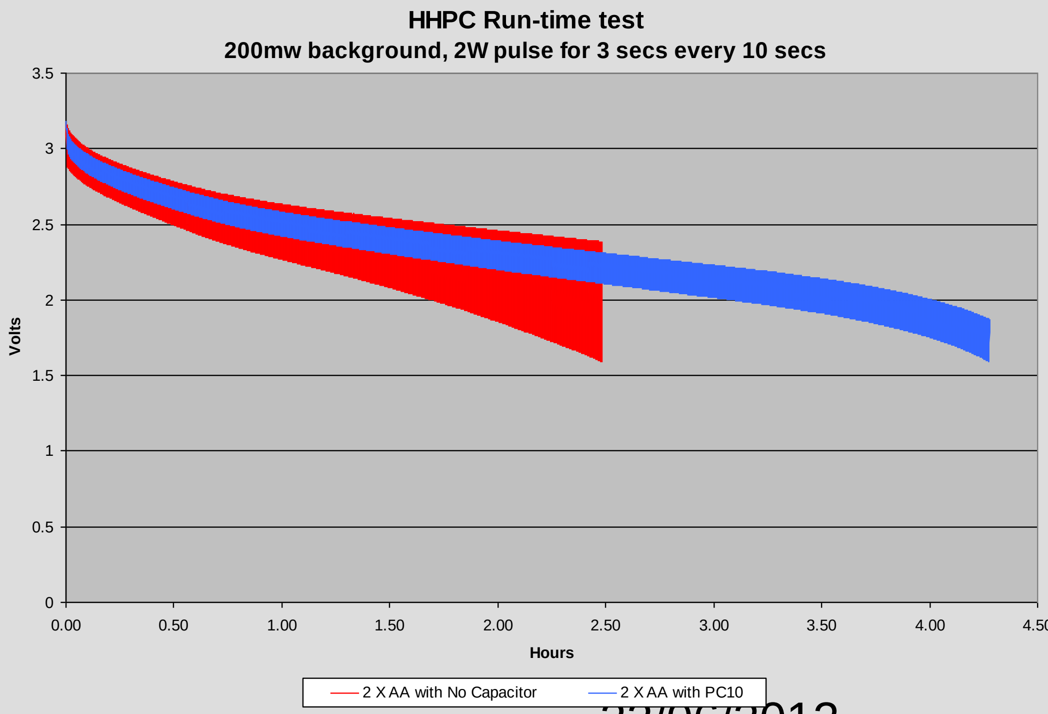


- High peak demands: Microprocessor activity, writing to disk and LCD operation
- Ultracaps across inexpensive alkaline batteries achieve the same life cycle as expensive new high power batteries
- The number of cycles are the same throughout the life of the camera
- The voltage drop is decreased and maintained constant over the cycle life
- Ultracaps make the camera smaller, lighter, and truly portable

Battery lifetime extension

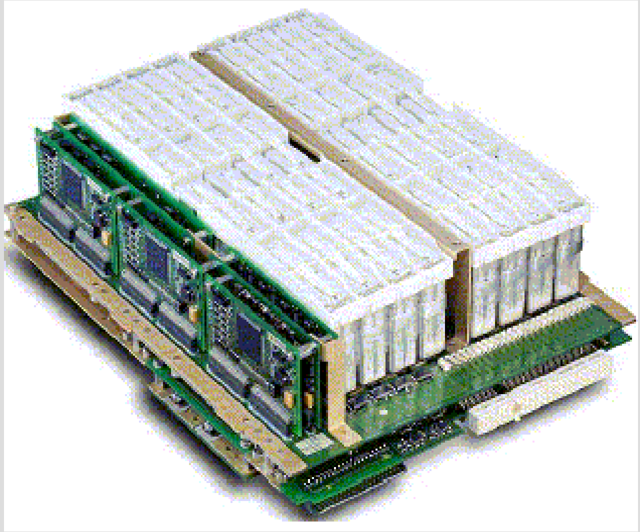






A380 Door Emergency Power Supply

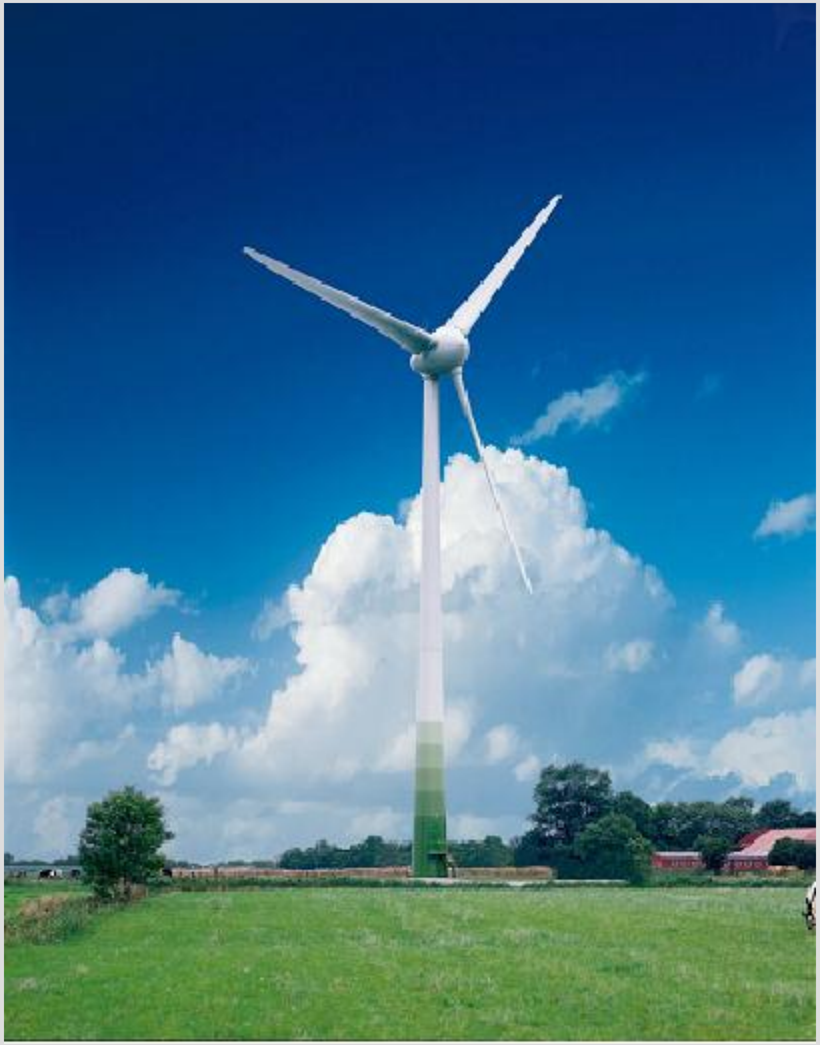
- Emergency actuation of 16 doors and Slide Management System (DSMS) actuators on the Airbus 380 incorporates ultracapacitor cells in a redundant configuration
- 2 main doors in permanent use for boarding, 14 rescue doors for emergency use
- 54 ultracaps per door
- 130 VA



- Doors must open on ground, in normal operation and emergency
- Doors must stay closed and locked in flight
- Slides must be inflated when required in emergency

Medium Size Wind Turbines

Ultracapacitor emergency power supply systems for 250 kW to 2 MW class wind turbines using 350 F D cell ultracapacitors



Enercon E-48:
Wind mill with 800 kW
- **Rotor diameter 48 m**
- **Hub height 50 to 76 m**

Static Energy Storage System

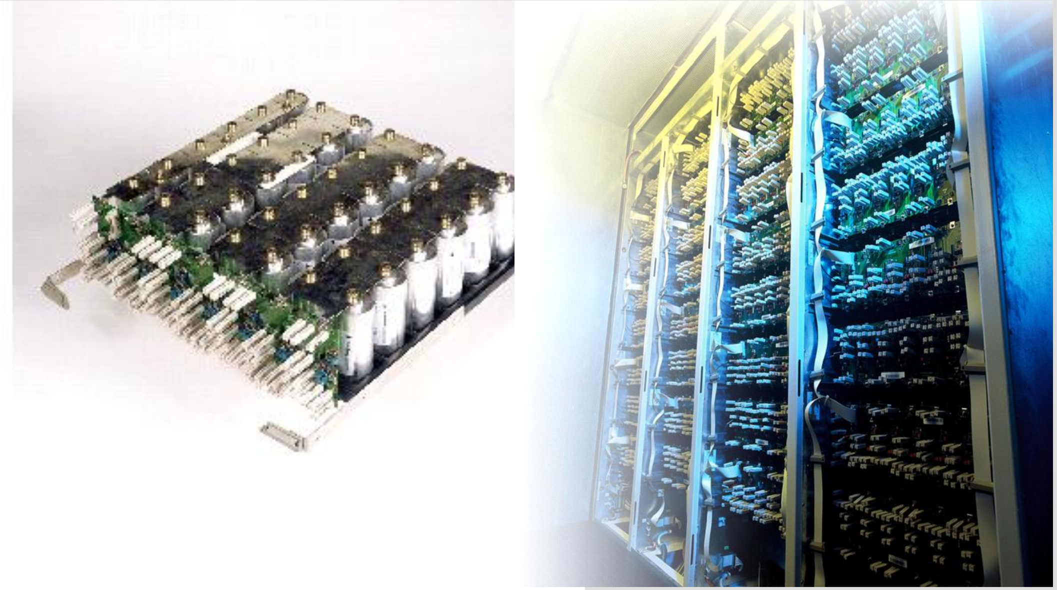
Working voltage: 750 VDC

Rated voltage: 790 VDC

Configuration:	7 blocs with 42 cells
# of Ultracapacitors:	294 BCAP series Dia 60mm
Balancing:	Passive
Monitoring:	Dedicated (U,I,T) CanBus
Cooling:	Forced air cooling
Protection:	IP
Footprint:	standard 800x600 mm
Heigth:	2000 mm total

SITRAS® Energy Storage System

Nominal voltage	DC 750 V
Nr of Ultracapacitors	1344
Stored energy	2,3 kWh
Energy saving per h	65 kWh/h
Max. power	1 MW
Capacitor efficiency	0,95
Temperature domain	–20 to 40 °C

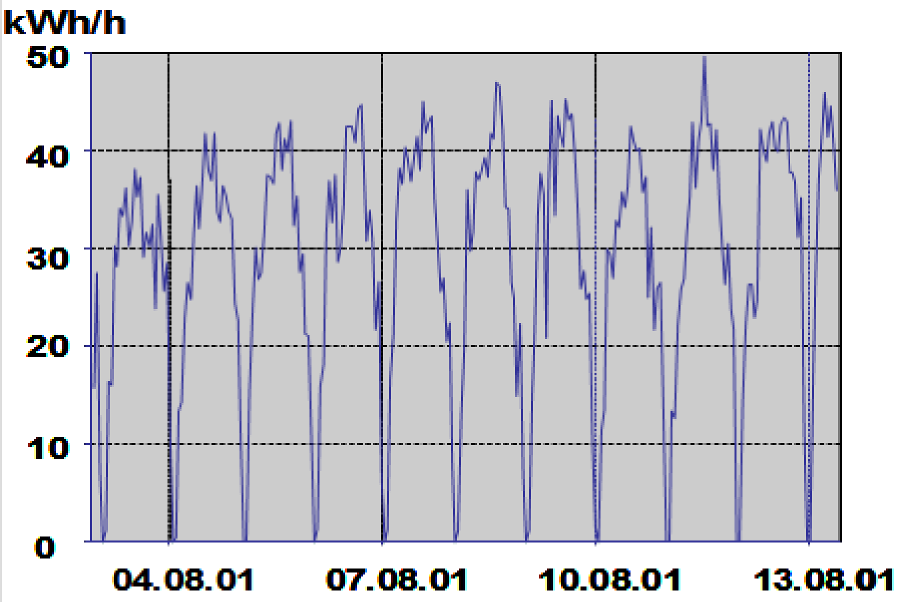


Energy saving operation

- Energy savings of 320 MWh per year
- Cost reduction (power-oriented operation costs, continuous and peak power)

Voltage stabilization operation

- No network voltage drop below critical level



MITRAC Bombardier Transport

600 * 2600F

Weight: 450 kg

Volume:

1900 x 950 x 455 mm

Benefits with ultracapacitors:

- Increase substation distance to 1.4…1.7 times
- or: reduce overheadline cross section (costs, visual impact)
- or: more vehicles in existing networks
- or: more powerful vehicles (longer)

Hybrid Electric Buses

- 2009 April: Maxwell Technologies, has received purchase orders worth a total of $13.5 million from three transit bus manufacturers in China for its 48 volt BMOD0165 P048 BOOSTCAP® ultracapacitor modules. They will be used to support braking energy recuperation and torque assist functions in **850** diesel-electric hybrid buses.

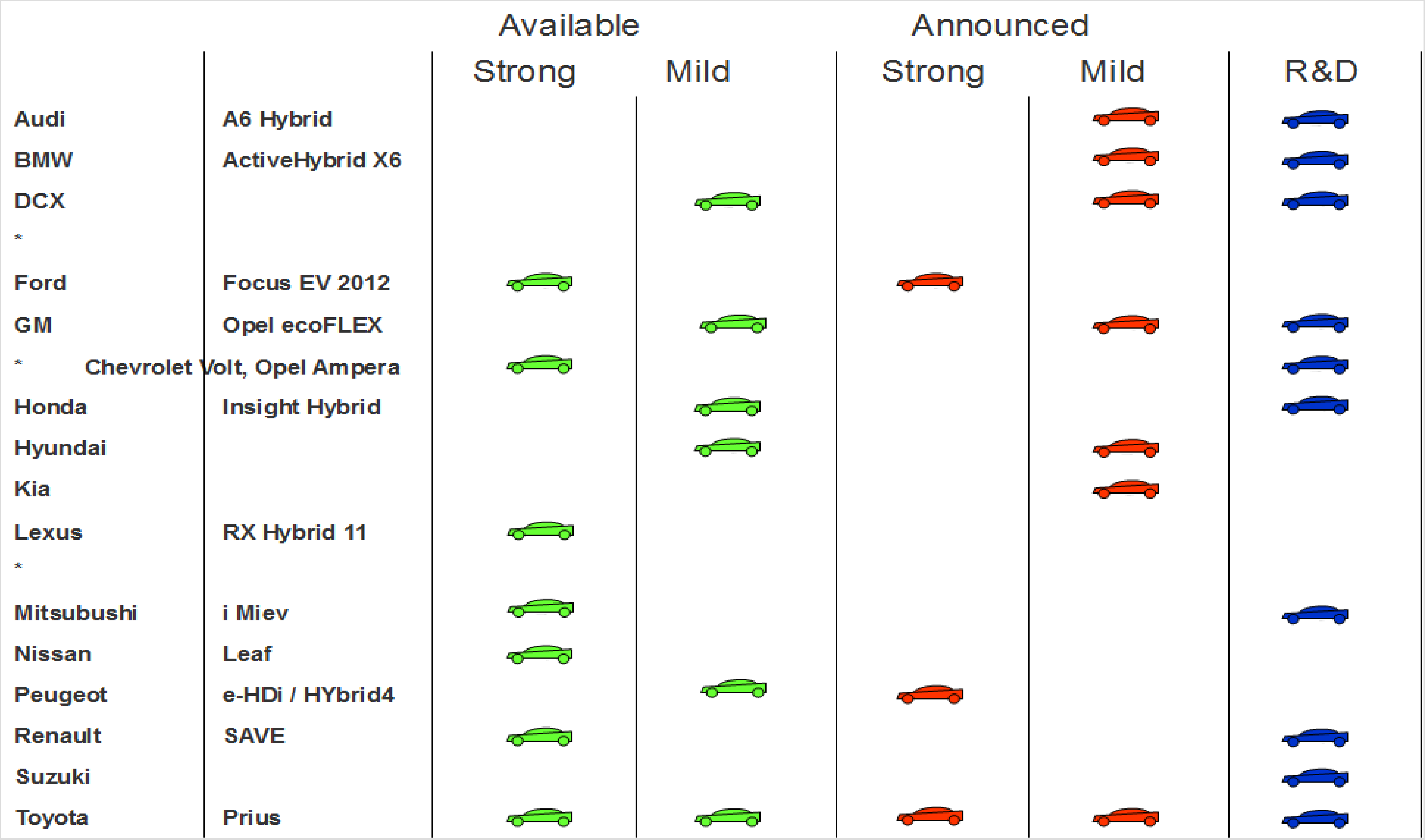
According to Frost & Sullivan as of December 2009, the estimated global hybrid and electric heavy commercial vehicle demand, which represents part of the addressable market for energy storage systems, is expected to reach approximately 240,000 units produced by 2015.

- 2010 Jan: ISE's ultracapacitor-based gasoline-electric hybrid bus drive systems now power nearly **300** buses in daily revenue service.
- 2010 Sept: **2'400** hybrid transit bus equipped with Boostcap in service
- 2011 Jan: 15 new Van Hool hybrid-trolleybus, with electrical equipment of Vossloh Kiepe (720 V, 200 kW), to complete the **30** vehicles in use for 1 year of the Azienda Trasporti Milanesi.

Hybrid - Variety

	Full-Hybrid	„Active“ Hybrid	Mild-Hybrid	Micro-Hybrid	Boardnet Stability
Start-Stop	●	●	●	●	
Regen	●	●	●		
Active Boost	●	●			
Electrical Drive	●				
Auxiliary users			●		●
Saving	~ 20 %	~ 15 %	~ 10 %	~ 5 %	
E-Motor	25 … >50kW		< 15 kW		
Voltage range	>300V		< 60 V		14 V +

OEM Hybrid Programs



PSA Stop-start

Using a micro-hybrid e-HDi technology with a new **VALEO** 2.2kW 3-phases synchronous starter-alternator reversible system (i-StARS) and a **Continental** “E-Booster” system containing **MXWL** supercapacitors, PSA offers diesel cars that:

- consume up to 15% less fuel in city driving
- reduce CO2 and other emissions by an equivalent amount (5 g/km).
- reduce the size of the battery by 30%, making it small enough to be located under hood instead of in the trunk.
- eliminates 6 m of heavy, expensive, copper battery cable and reduce wiring complexity and assembly labor, partially offsetting the cost of the stop-start system components.
- boosts the battery to drive the reversible alternator at start.
- make engine noises practically unnoticeable.
- provides 70 % more torque than the previous generation (53 Nm).
- engine restarts in just 400ms,
  - twice as fast as a manual key restart.
  - 30 % faster than with a reinforced starter (dual mass flywheel (DMF)).
- Volt Control alternator management system to regenerate energy as the vehicle slows.

- 5 volts of stored energy in 2 series connected 1200 F supercapacitors,
- 180 A, 400 ms,
- Durability: 600,000 restarts,
- Efficiency >77%.
- -5◦C to 30◦C

http://www.psa-peugeot-citroen.com/document/presse_dossier/PressPack_e-HDi_GB1276078007.pdf

Honda FCX fuel cell

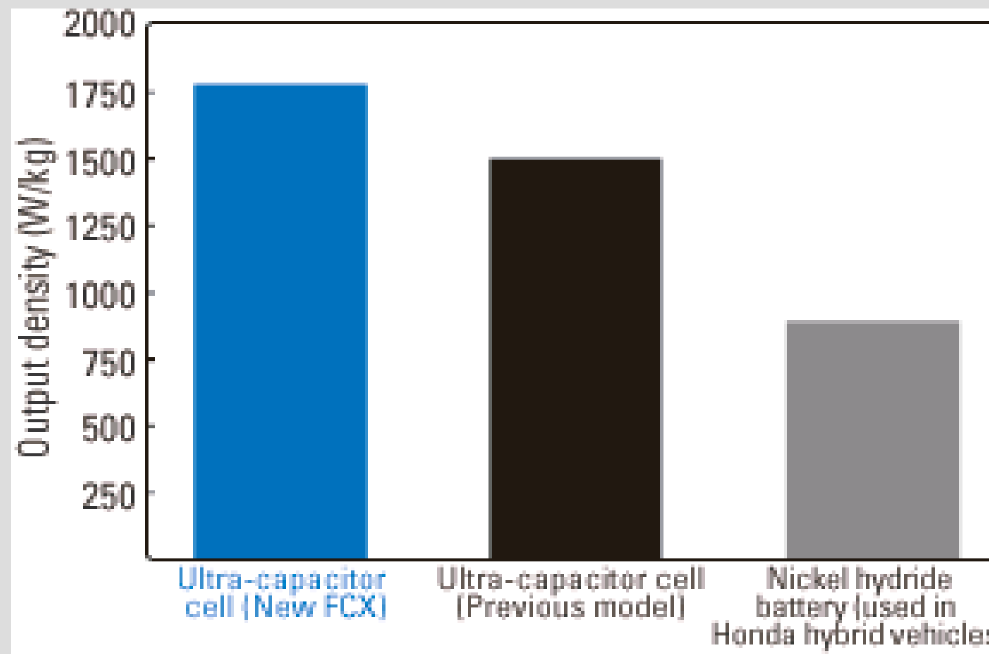
Specifications
Number of passengers 4
Motor Max. Output 95kW (129PS, 127 horsepower)
Max. Torque 256N•m (26.1kg•m, 188.8 lb-ft.)
Type AC synchronous motor (Honda mfg.)
Fuel cell stack PEFC (proton exchange membrane fuel cell, Honda Mfg.)
Output 100kW
Fuel Type Compressed hydrogen
Storage High-pressure hydrogen tank 350 atm
Tank Capacity 171 liters
Dimensions (L×W×H) 4,760 × 1,865 × 1,445mm

Max. Speed 160km/h
Energy Storage Lithium Ion Battery
Vehicle Range* 570km (354 miles)
* When driven in LA4 mode (Honda calculations)

The new FCX available for limited purchase in 2008.

Honda ultra-capacitor (system module)

Honda has independently developed a high-performance ultra-capacitor (electrical two-layered condenser) to serve as a supplementary power source to the FCX's main power source - the fuel cell stack - for more powerful performance under various driving conditions.



http://world.honda.com/FuelCell/FCX/ultracapacitor/

toyota supra hv-r hybrid electric capacitor ultracapacitor

TOYOTA: FIRST MOTOR RACE WIN WITH A HYBRID CAR
Toyota made history in 2007 by winning the Tokashi 24-Hour Race with its Supra HV-R hybrid race car. It is the first time ever that a Hybrid race car has won a competition. The Supra's success follows an entry last year when Toyota was the first car manufacturer to enter a hybrid vehicle – the Lexus GS450h – into the Tokashi 24-Hour race which finished 17th overall.

1. Three electric motors
A four-wheel energy regeneration and drive system has been adopted which includes in-wheel motors in the front wheels in addition to one 150 kW rear-axle mounted electric motor.

2. Specially Designed Capacitor
In light of the fact that racing involves a repeated acceleration and deceleration under full system performance, a quick-charging capacitor system was adopted instead of the usual rechargeable batteries.

KERS system

- Li bat — McLaren, Williams
- Multi-layer ceramic capacitors (BaTiO3 Murata Magneti Marelli) — Ferrari, Renault
- Flybrid System (Flywheel + capacitors Magneti Marelli) — Williams
- Flywheel
- Supercapacitor

- Today 24 kg batteries (343 cells) from supplier A123 would be able to produce 60 kW, but need about 20 kg of super-capacitors (assuming 10 kW/kg specific power) to soak up the braking energy in the short periods of vehicle retardation and then release this over the rest of the lap to charge the batteries.
- 45 kg seems a reasonable estimate for a battery/capacitor energy store of 2.5 MJ.

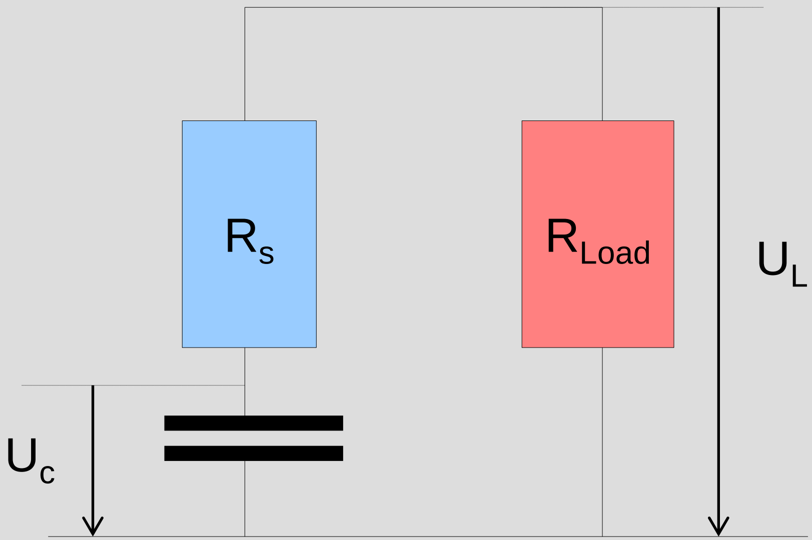
- In a 'long' 5 second braking event, 1 MJ of energy can be generated by the 200 kW maximum input limit.
- The requirement to absorb 200 kW results in 20 kg of super-capacitors, assuming 10 kW/kg,

http://paddocktalk.com/news/html/modules/ew_filemanager/07images/f1/fia/332668895__2011_Power_Train_Regulation_Framework.pdf

Storage system efficiency

- Electric model
- Ragone Plot
- Efficiency

Basic electrical model



$$\begin{cases} U_L = R_L\, i \\ U_L = U_c - R_s\, i \end{cases}$$

$$U_c = U_L \left(1 + \frac{R_s}{R_L}\right)$$

- Series resistance contributors:
  - Electronic — Ionic
    - Conductors — Separator
    - Collector — Electrolyte
    - Carbon

Definitions

- W_s is the energy dissipated in the storage component
- W_L is the energy used in the Load
- W_{max} is the maximum energy stored in the component

$$W_{\max} = \frac{1}{2} C U_{c\max}^2$$

- This stored energy can be transferred to the load with a good efficiency only with small currents. In that condition, the Joule dissipation in the internal resistance of the component W_s is minimized

Energy available in the load

$$\left.\begin{array}{l} W_L = R_L \int i^2 dt \\ W_s = R_s \int i^2 dt \end{array}\right\} W_{max} = W_L + W_s = (R_L + R_s)\int i^2 dt$$

$$W_L = \frac{R_L}{R_L + R_s} W_{max}$$

With: $\alpha = \frac{R_L + R_s}{R_s}$, $\alpha > 1$

$$W_L = \frac{\alpha - 1}{\alpha} W_{max}$$

- α -> 1 : R_L -> 0, max current, power remains in the capacitor
- α = 2 : match impedance
- α >> 2 : low current, low power

Power and available energy at match impedance

- In the particular case of impedance matching, the power used in the load and the power dissipated in the internal resistance are equal.

$$R_s = R_L \quad \Longrightarrow \quad P_m = P_s = P_L = U_L\, i = U_L \frac{U_L}{R_L} = \frac{U_L^2}{R_s}$$

$$U_L = \frac{U_c}{2} \quad \Longrightarrow \quad P_m = \frac{U_c^2}{4R_s}$$

$$W_m = \frac{W_{\max}}{2} \qquad P_m = \frac{U_c^2}{4R_s} = \frac{W_{\max}}{2R_sC} = \frac{W_{\max}}{2\,\tau_o}$$

- Where τ_o is the technology time constant

Power available for the load

$$P_L = \frac{U_L^2}{R_L} = \frac{U_c^2}{R_L}\left(\frac{R_L}{R_L + R_s}\right)^2 = U_c^2 \frac{R_L}{(R_L + R_s)^2} = \frac{U_c^2}{4R_s}\frac{4R_s R_L}{(R_L + R_s)^2}$$

$$P_L = 4P_m \frac{\alpha - 1}{\alpha^2}$$

- With the introduction of the **efficiency** definition as the ratio between the energy available for the load and the maximum stored energy in the component

$$\beta = \frac{W_L}{W_{\max}} = \frac{\alpha - 1}{\alpha^2}$$

- The power in the load is now given as a function of the maximum power available at match impedance P_m by

$$\frac{P_L}{P_m} = 4\beta(1 - \beta)$$

Ragone equation

- Solving the 2nd degree equation of the power $\frac{P_L}{P_m} = 4\beta(1-\beta)$

- With $\beta = \frac{W_L}{W_{\max}}$

- The energy available in the load W_L as a function of the power available in the load P_L may be plot with the following relation:

$$W_L = \frac{W_{\max}}{2}\left(1+\sqrt{1-\frac{P_L}{P_m}}\right)$$

with

$$\begin{cases} P_m = \dfrac{W_{\max}}{2\,\tau_o} \\ \tau_o = R_s C \end{cases}$$

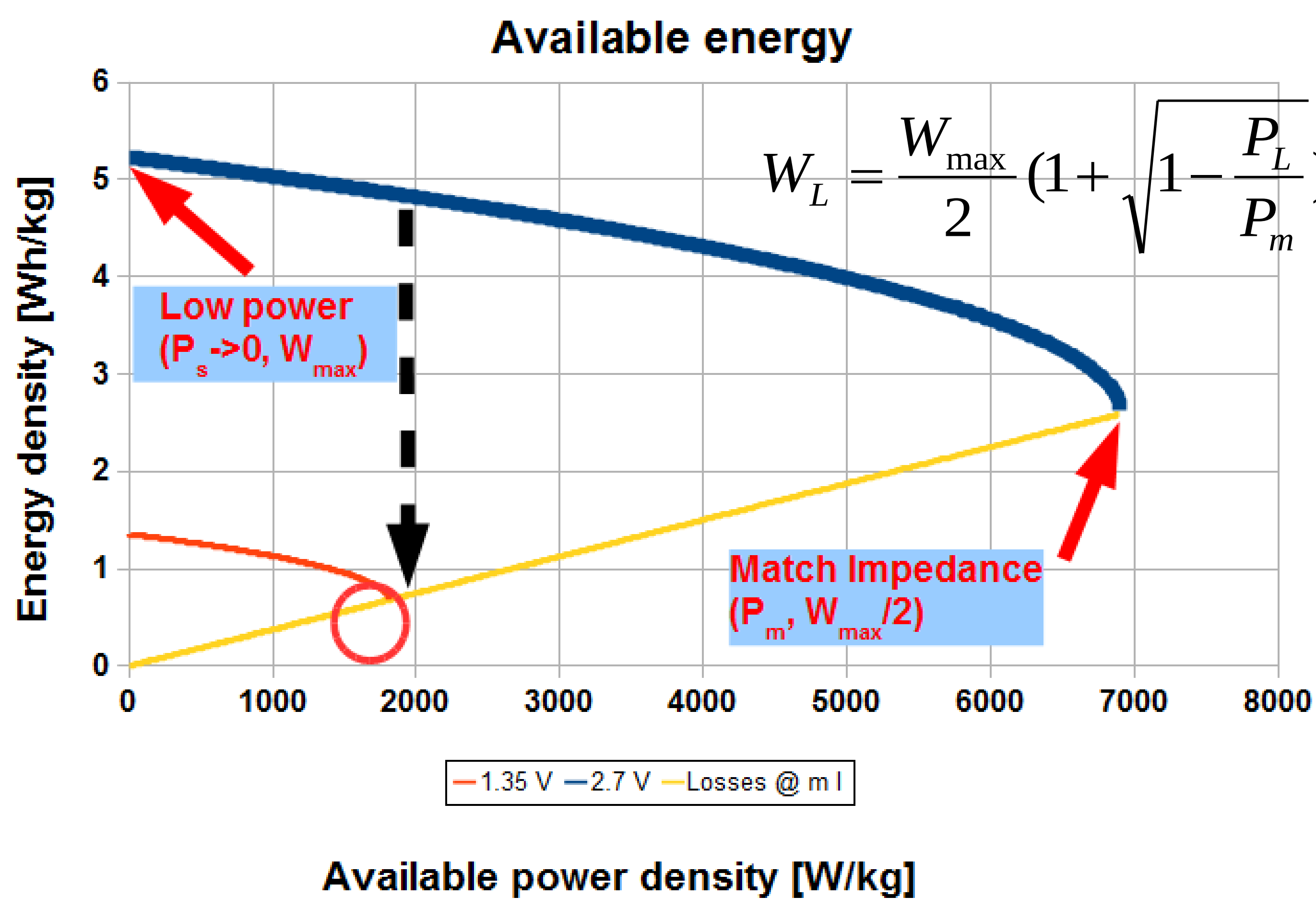
Example for a supercapacitor

- U_c = 2.7 [V]
- C = 310 [F]
- R_s = 2.2 [mOhm]
- M = 60 [g]

=> τ_o = 0.68 [s]

=> W_{max} = 1130 [J]

=> P_m = 828 [W]



$$W_L = \frac{W_{max}}{2}(1+\sqrt{1-\frac{P_L}{P_m}})$$

Power dissipated

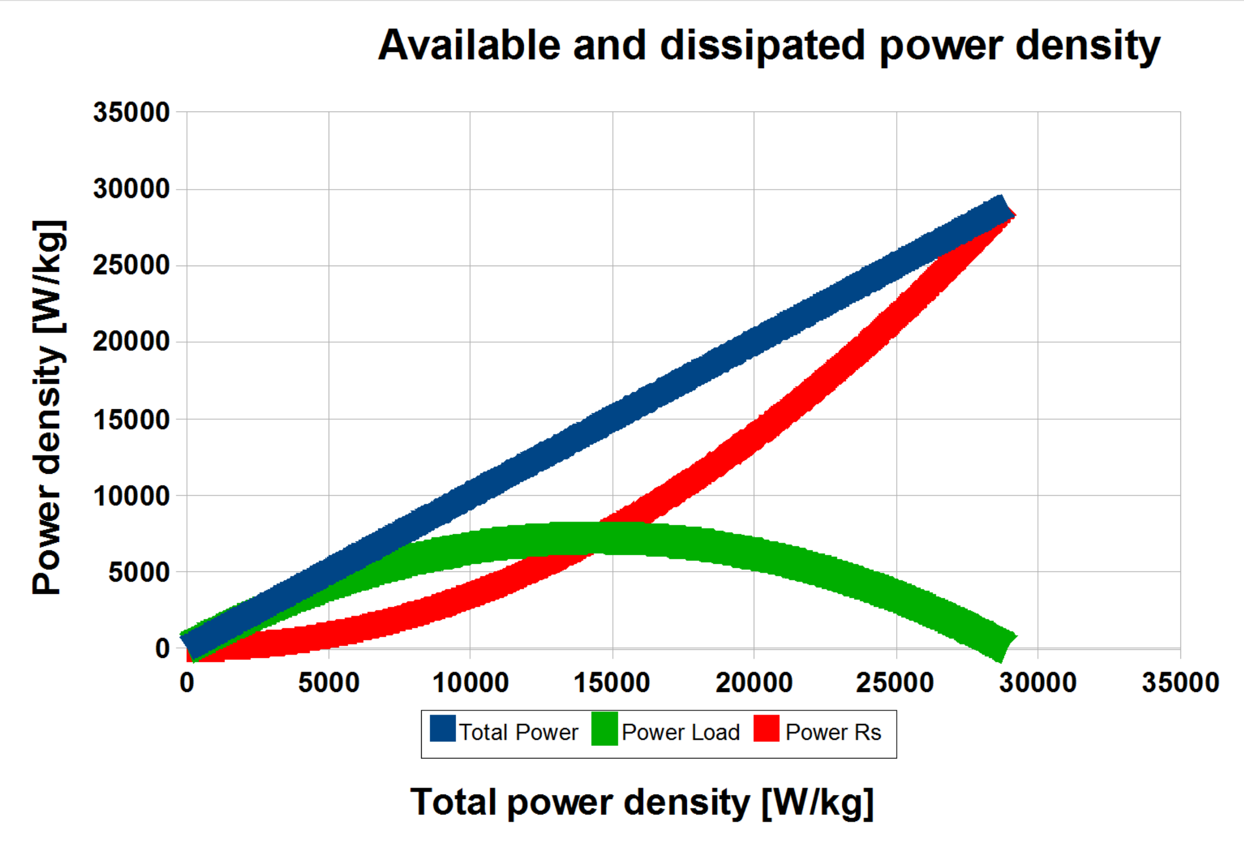
- Total power

$$P_{total} = P_L \frac{W_{\max}}{W_L}$$

- Power and energy dissipated

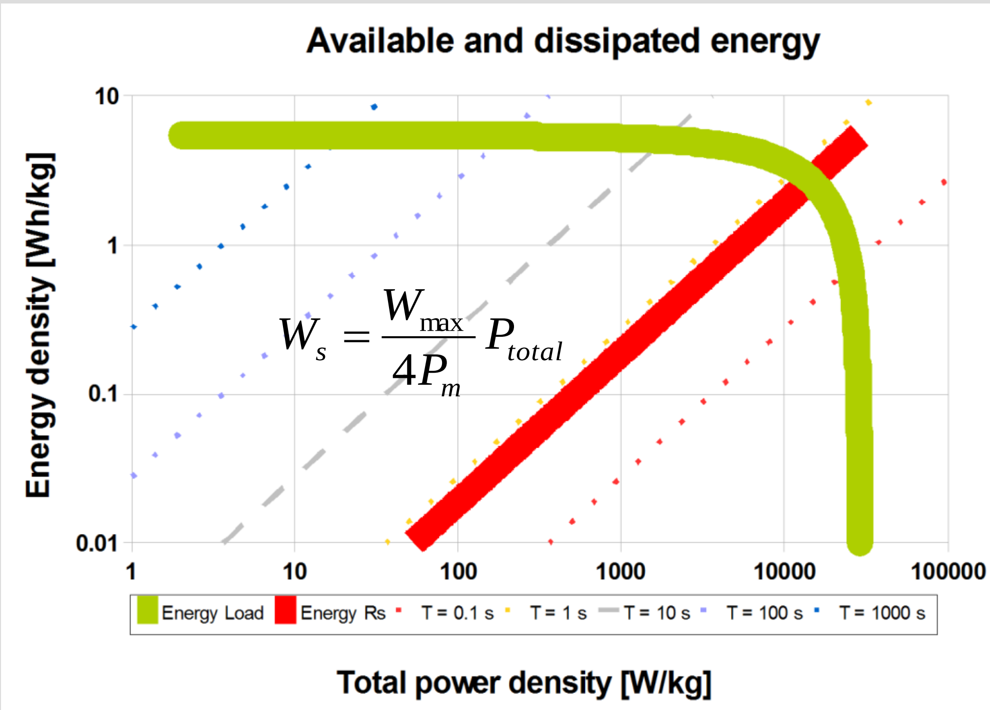
$$P_s = P_L \frac{R_s}{R_L} \qquad W_s = \frac{W_{\max}}{4P_m} P_{total}$$

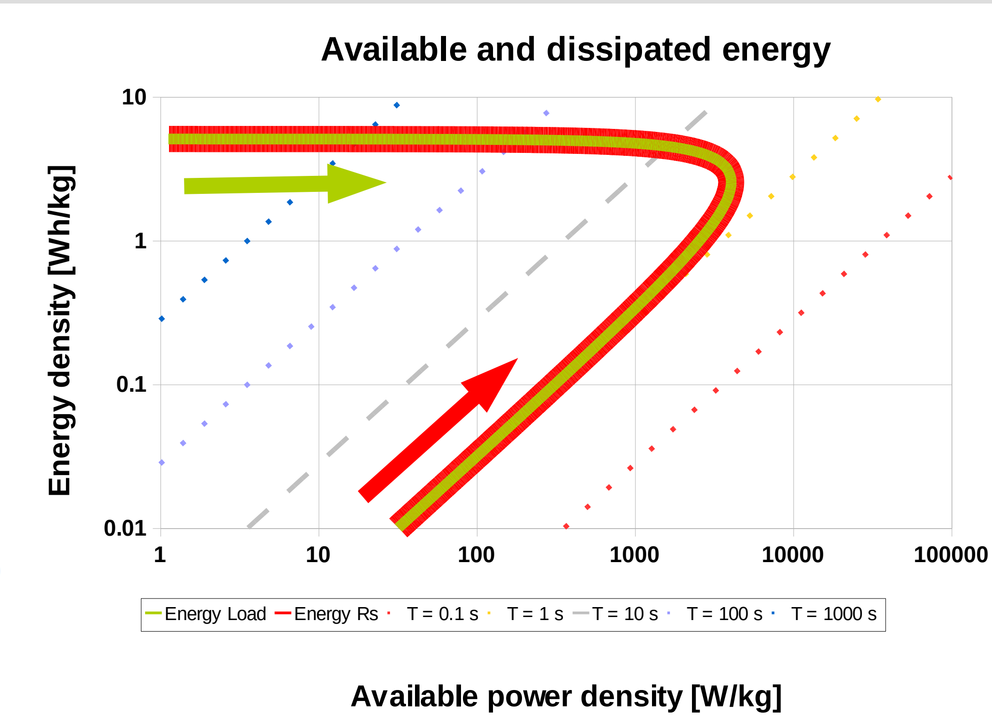
Available and dissipated Power



Plot of the load available power and the series resistance dissipated power as a function of the sum of the load available power and the series resistance dissipated power.

Energy fct of available and total Power





- Ragone plot representing the available energy and the dissipated energy as a function of the total and available power.
- *At matched impedance the power ratio is 2 (7 to 14 kW)*
- *At low power, the power ratio is close to 1*

Storage System Design

-

Reliability

Reliability, Safety, Security

- **Reliability**: ability of an entity to perform under NORMAL conditions
- **Safety**: ability of an entity to perform under ABNORMAL conditions
- **Security** (ability of an entity to perform in the presence of MALEVOLENT environment)
- **Reliability Prediction:** A reliability prediction is simply the analysis of parts and components in an effort to predict and calculate the rate at which an item will fail. A reliability prediction is one of the most common forms of reliability analyses for calculating failure rate and MTBF.

Failure definition

Failure is defined as the lack of ability of a component, equipment, sub system, or system to perform its intended function as designed. Failure may be the result of one or many faults.

Applied to the supercapacitors, the failures may be :

- Capacitance loss greater than 20%
- Series resistance increase bigger than 100%
- Leakage
- Cell opening

Causes – failure mode - consequences

Supercapacitor failure modes

- **Causes**
  - Aging (normal)
    - High voltage
    - High temperature
  - Overvoltage (abnormal)
  - Fire (abnormal)
  - Shocks and vibrations
- **Modes**
  - Capacitance decrease
  - ESR increase
  - Temperature increase
  - Gas generation
  - Overpressure
  - Capa/ESR out of spec.
  - Cell leakage (solvent vapor release)
  - Cell opening
- **Consequences**
  - Vehicle stopped
  - Vehicle damaged
  - Loss of performance

Risk evaluation: FDG

- F   failure frequency
- D   failure non-detectability
- G   failure gravity
- R = F x D x G

- F, G and D are numbers from 1 to 10 (for example)
- A FMEA is a procedure to reduce the risks
- The risks R are sorted by importance
- Actions: tests (D), re-design (F)

Failure rate

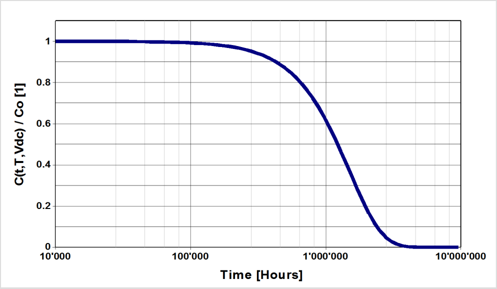
Example: Failure mode = cell opening

Failure rate

- Aging law (**Weibull**, exponential, log normal, ...)
- Survivor function
- Failure rate
- Derating T and V

Weibull model

The Weibull model is widely used in electrotechnics.



Survivor function

$$F(t) = \exp^{-(\lambda_o t)^p}$$

Probability density function

$$f(t) = \lambda_o \; p \, (\lambda_o t)^{p-1} \; \exp^{-(\lambda_o t)^p}$$

$$f(t) = \frac{d}{dt} F(t)$$

Failure rate

$$\lambda(t) = \lambda_o \; p \, (\lambda_o t)^{p-1}$$

$$\lambda(t) = \frac{f(t)}{F(t)}$$

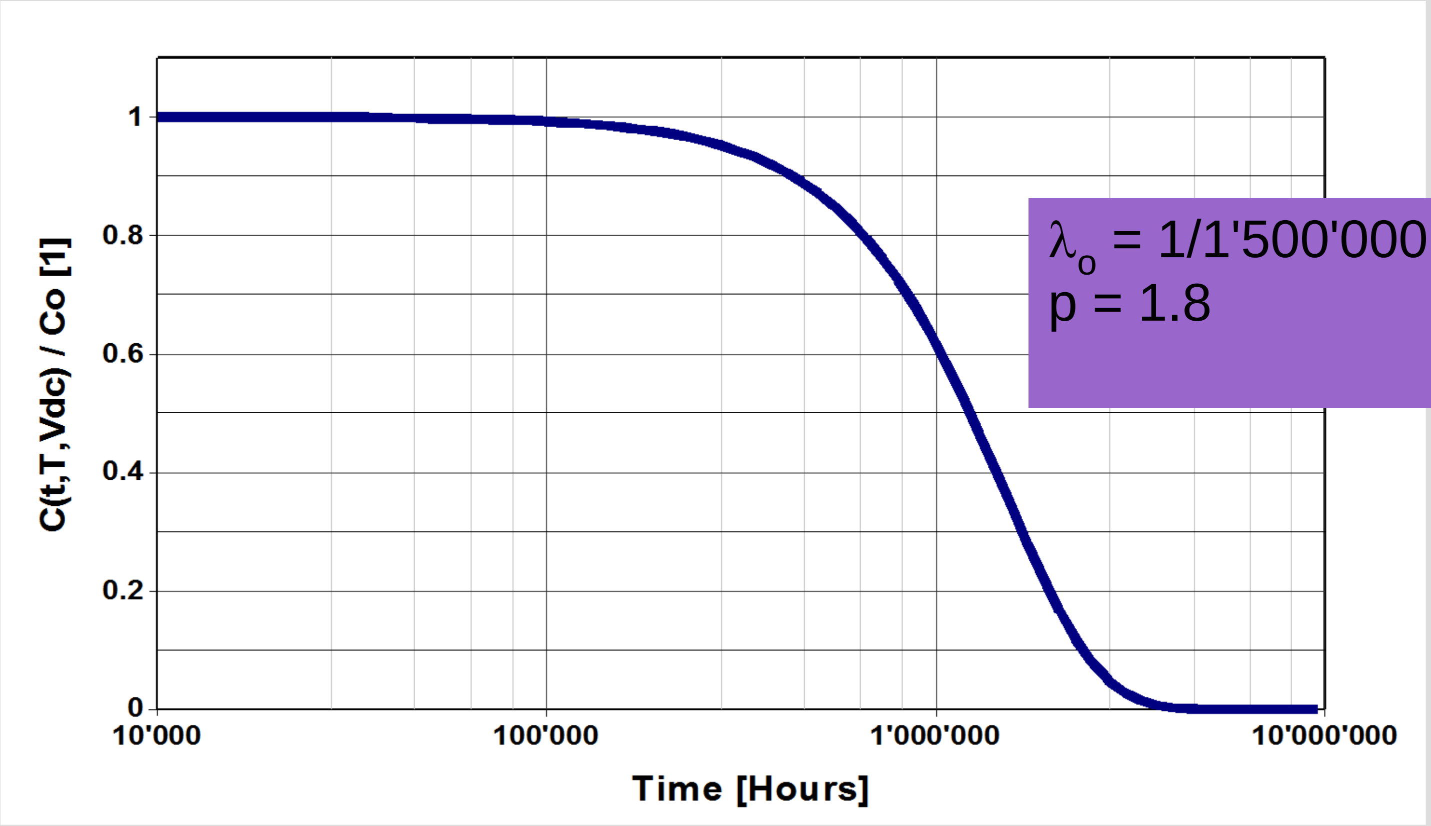
Mean Time Between Failures (MTBF)

$$MTBF = \frac{1}{\lambda_o}$$

If p is set to 1, it comes out that the exponential model is a particular case of the Weibull model

Weibull survivor curve

$$F(t) = \exp^{-(\lambda_o t)^p}$$

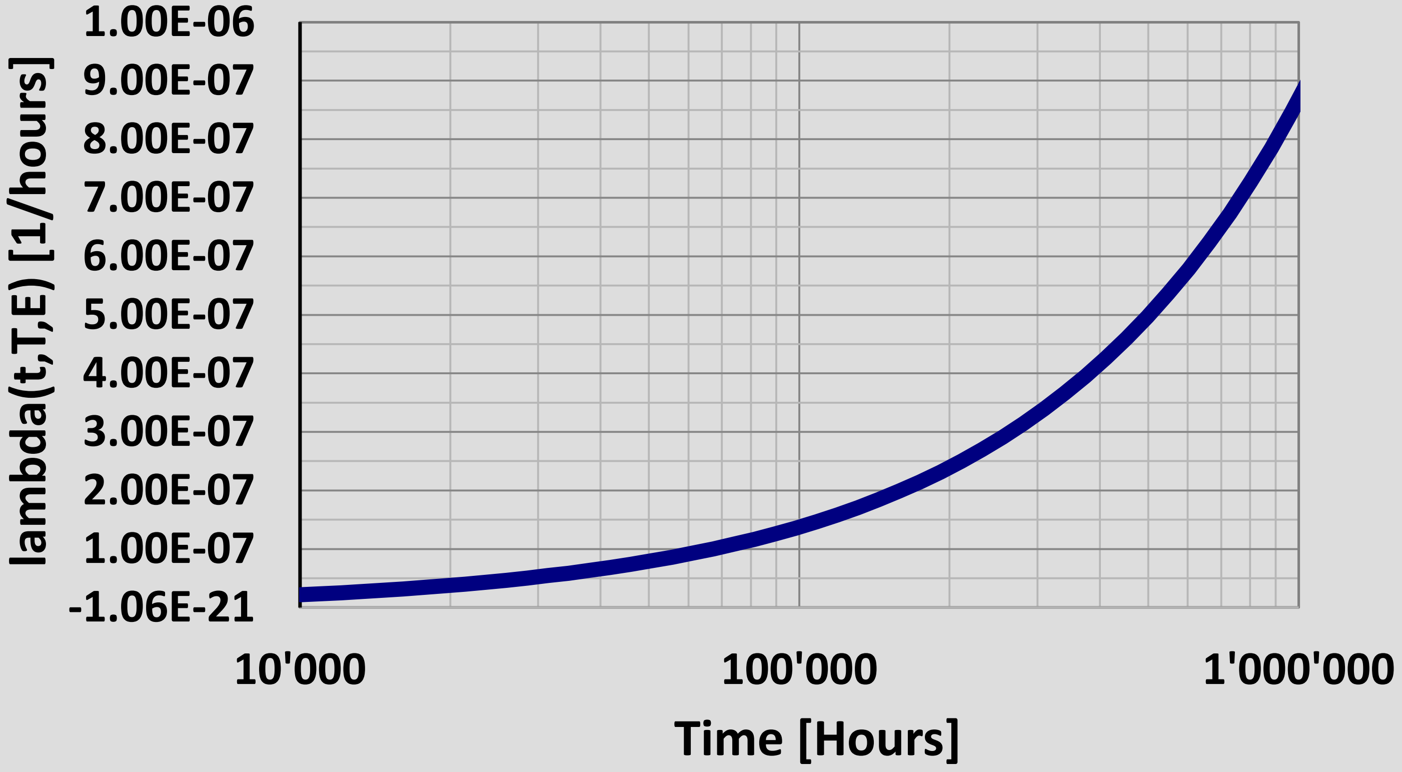


λ_o = 1/1'500'000 hours
p = 1.8

- The survivor function corresponds to the proportion of capacitors in the batch which didn't failed after the time t. It may also be considered as the remaining capacitance of a capacitor after a time t.

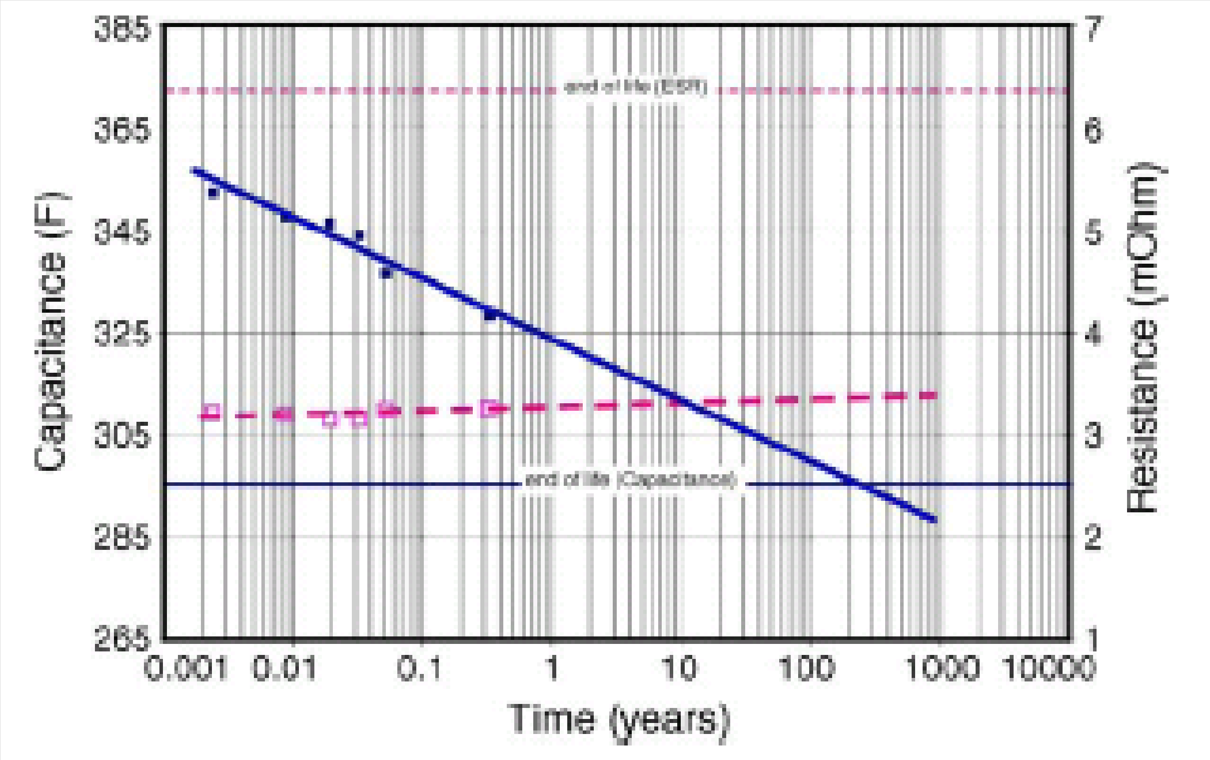
Weibull failure rate

$$\lambda(t)=\lambda_o\ p\,(\lambda_o t)^{p-1}$$



- The failure rate value given in the manufacturer specifications, as it is increasing with time, corresponds to the value for the end of life.

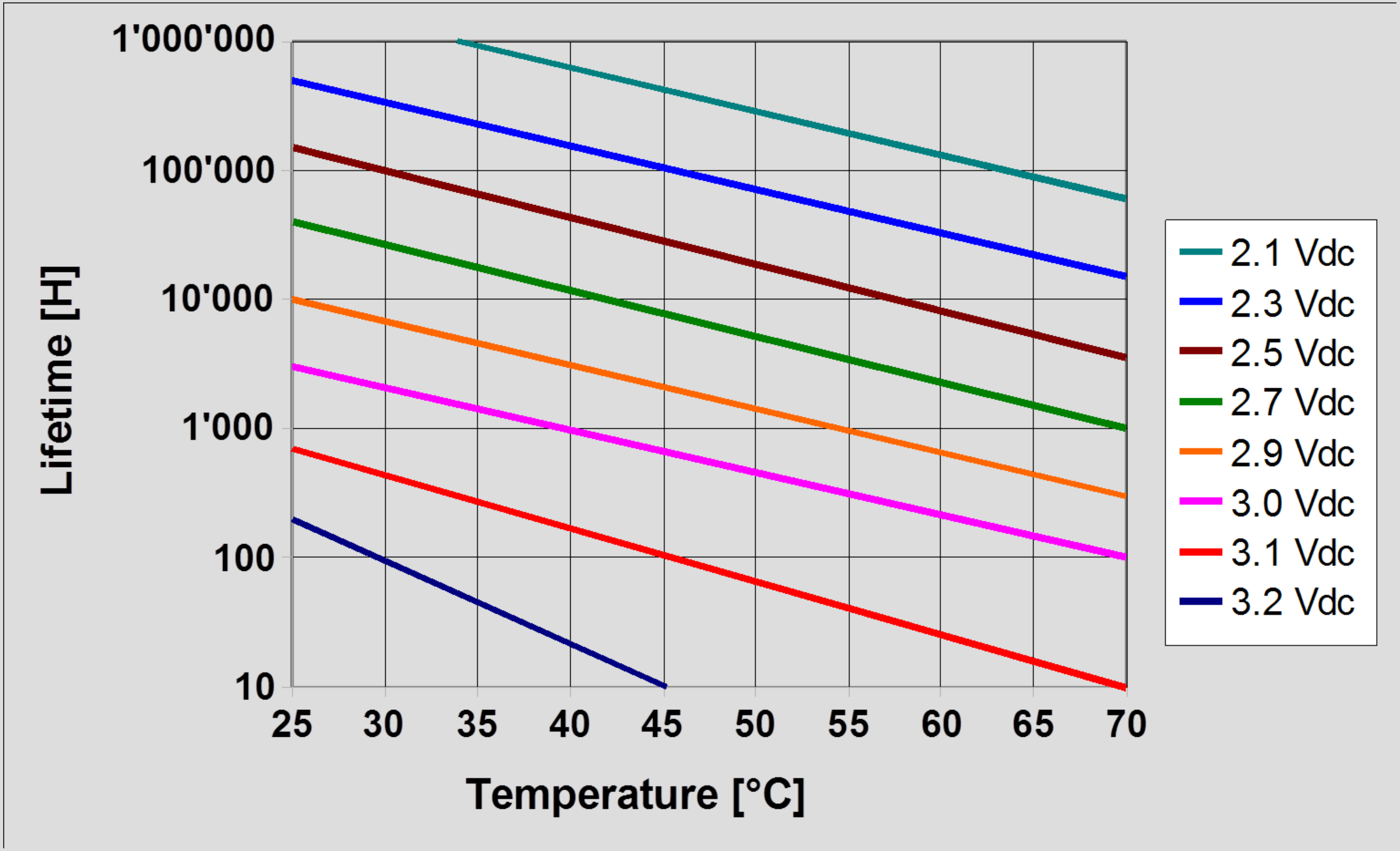
2.5 Vdc at Room Temperature



- BCAP0350 at RT and 2.5 Vdc continuous
- The lifetime of the capacitor is limited by the capacitance fading rather than by the increase in ESR. A linear extrapolation of the capacitance data results on a lifetime of more than 300 years until the capacitance decreases from 350 F by 20% to 280 F. Simultaneously, the increase in ESR is not significant.

PSI, J. Power Source 154 (2006) 550

Theoretical lifetime expectation



Measurement technics

- Charge/discharge at constant power or current
- Impedance spectroscopy

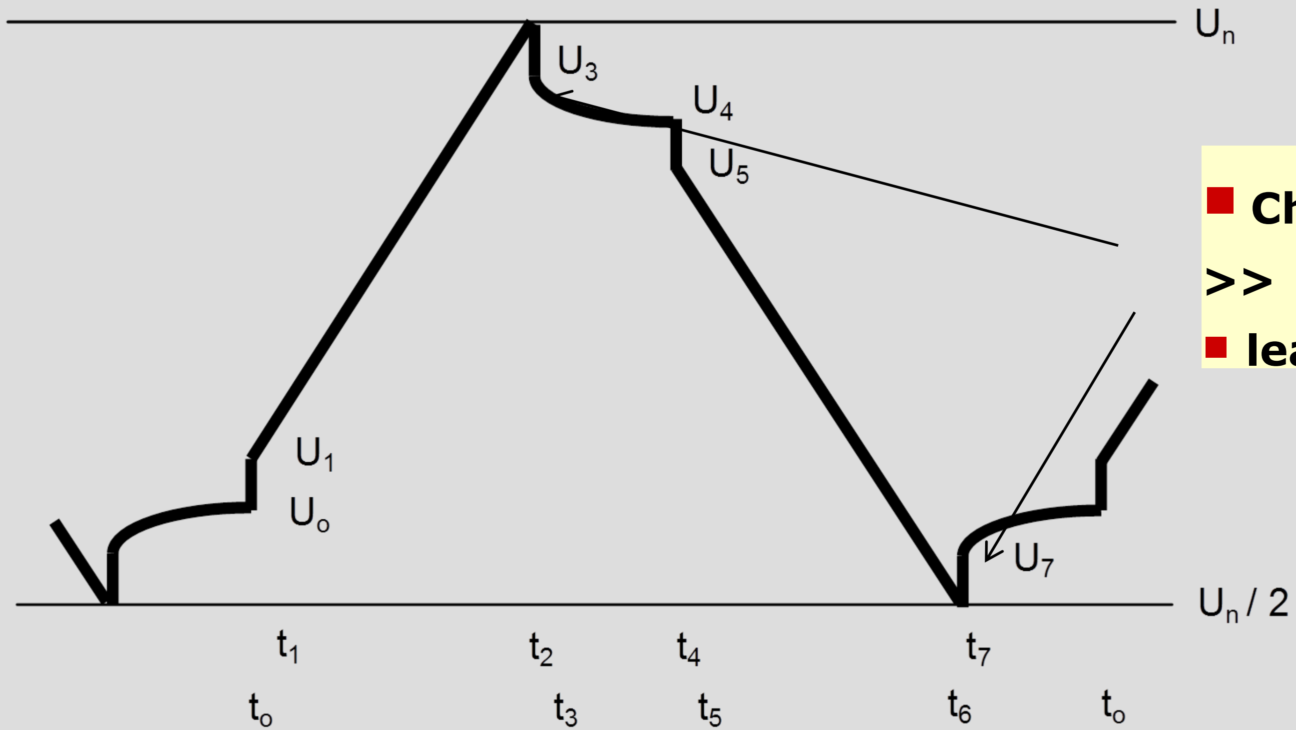
IEC 62391 standard

IEC 62391-1: Fixed electric double layer capacitors for use in electronic equipment - Part 1: Generic specification

IEC 62391-2: Fixed electric double layer capacitors for use in electronic equipment - Part 2: Sectional specification: Electric double layer capacitors for power application

IEC 62391-2-1: Fixed electric double layer capacitors for use in electronic equipment - Part 2-1: Blank detail specification: Electric double layer capacitors for power application. Assessment level EZ.

Capacitance and ESR measurement



- **Charge redistribution**

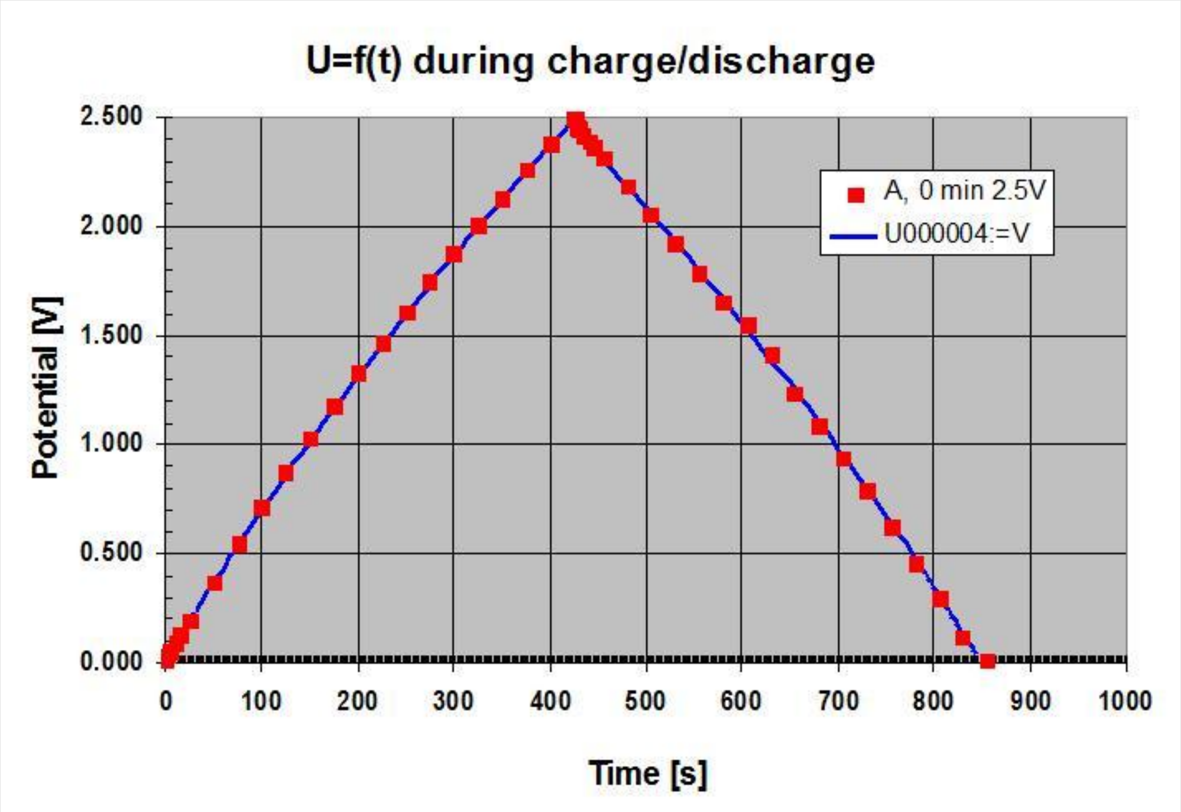
>>

- **leakage current**

- **C = I Δt / ΔU**
- $\mathbf{V_{drop} = R_s\ I}$

- C $_{charge}$: Time between t_0 and t_2
- C $_{discharge}$: Time between t_4 and t_6
- ESR $_{charge}$: Voltage drop between t_2 and t_3 @ U_n (MXWL: 2 s)
- EST $_{discharge}$: Voltage recovery between t_2 and t_3 @ U_{min} (MXWL: 2 s)

Capacitance and ESR measurement



1800 F
10 A

- $C = I \Delta t / \Delta U$
- $V_{drop} = R_s I$

The consequence of a voltage dependency of the capacitance may be also seen in the constant current charge profile. The voltage increase is no more linear. The slope is steeper at low voltage when the capacitance is smaller.

Constant power charge/discharge

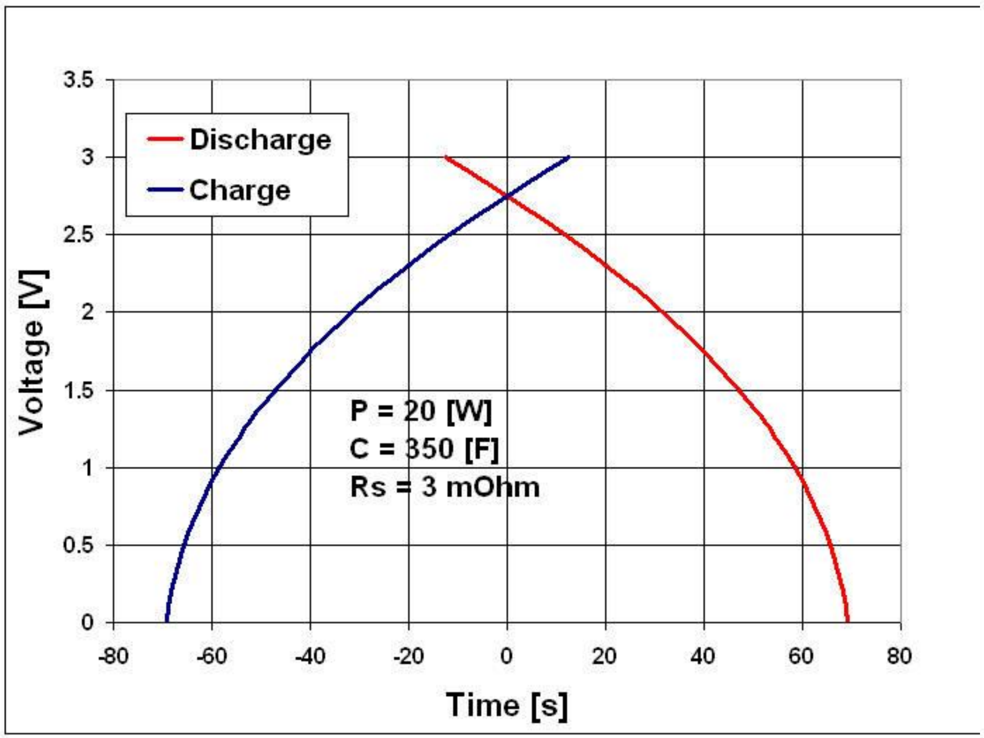
Let P be the constant power, C the capacitance, R the series resistance and x(t)the voltage.

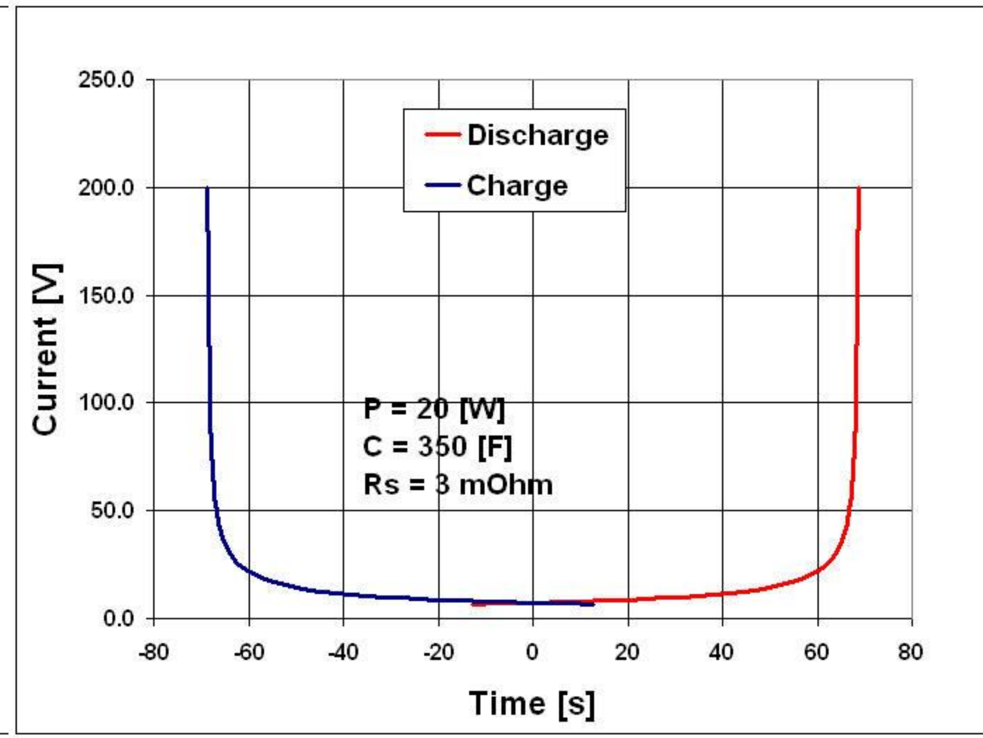
The equation to solve is

$$Rx'(t)^2 + \frac{1}{C}xx'(t) - P = 0.$$

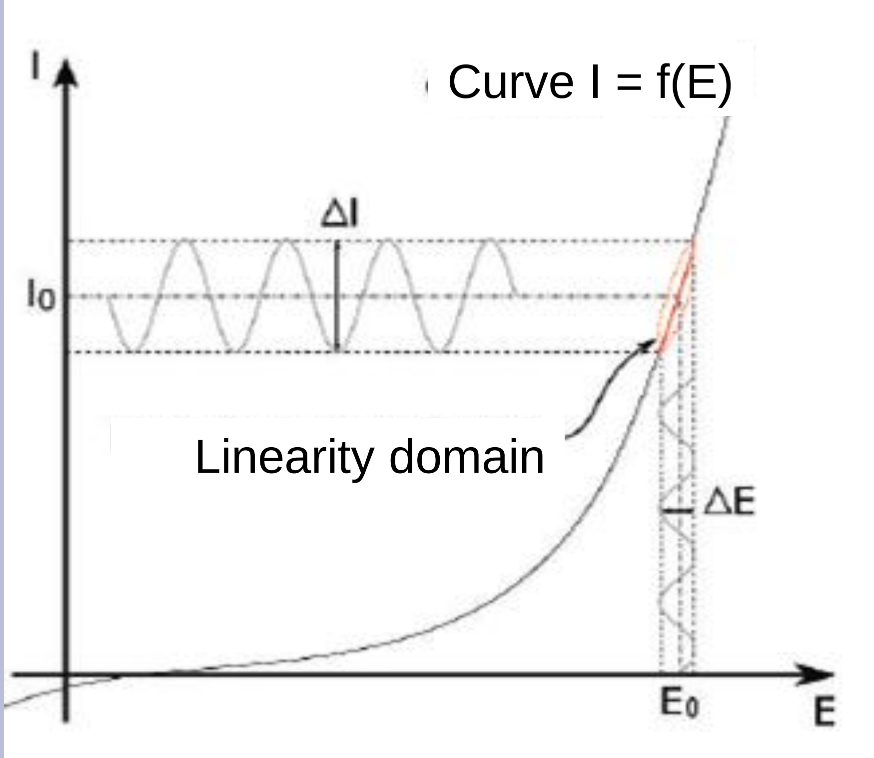
The solution is

$$\frac{4PR\ln\left(C\sqrt{\frac{x^2}{C^2}+4PR}+x\right)C^2 + x\left(C\sqrt{\frac{x^2}{C^2}+4PR}+x\right)}{4CP} = t + \text{constante}$$





Impedance spectroscopy



Potentiostatic mode: $\Delta E(\omega)$ is a ripple superposed to the potential E0, and $\Delta I(\omega)$ is the response in current of the system with a continuous component I0 .

Galvanostatic: in that case, a ripple current is superposed to the current and the potential response is measured.

The impedance $Z(\omega)$ is a complex number which may be written in 2 equivalent ways :

$Z(\omega) = |Z(\omega)|\, e^{j\Phi(\omega)}$ where
$Z(\omega) = Z_r(\omega) + jZ_j(\omega)$ with $j = \sqrt{-1}$,

$|Z|$ is the impedance module, Φ the phase, Z_r the real part and Z_j the imaginary part.
These values are connected with the following relations :
$|Z|^2 = Z^2_r + Z^2_j$ and $\Phi = \tan^{-1} Z_j/Z_r$
where $Z_r = |Z| \cos \Phi$ and $Z_j = |Z| \sin \Phi$

Impedance spectroscopy

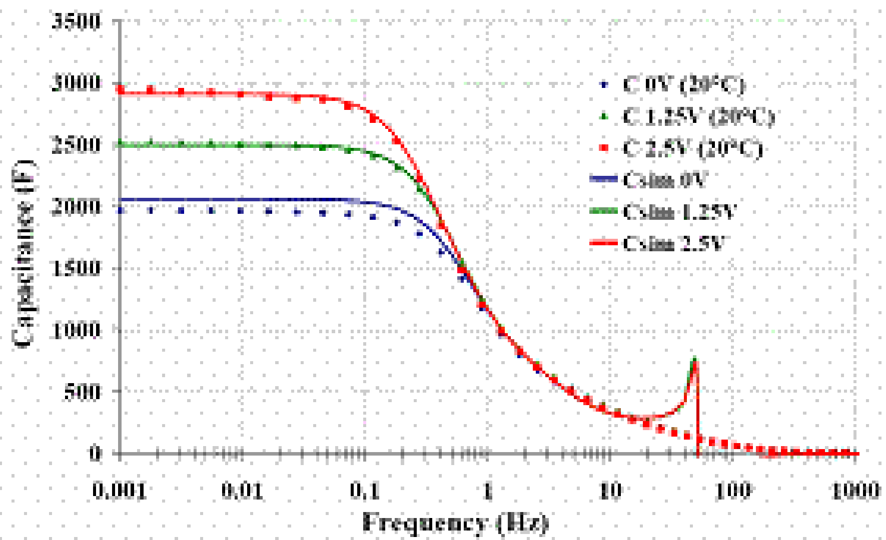


Figure 1: BCAP0010 capacitance frequency spectrum for 3 different polarization voltages.

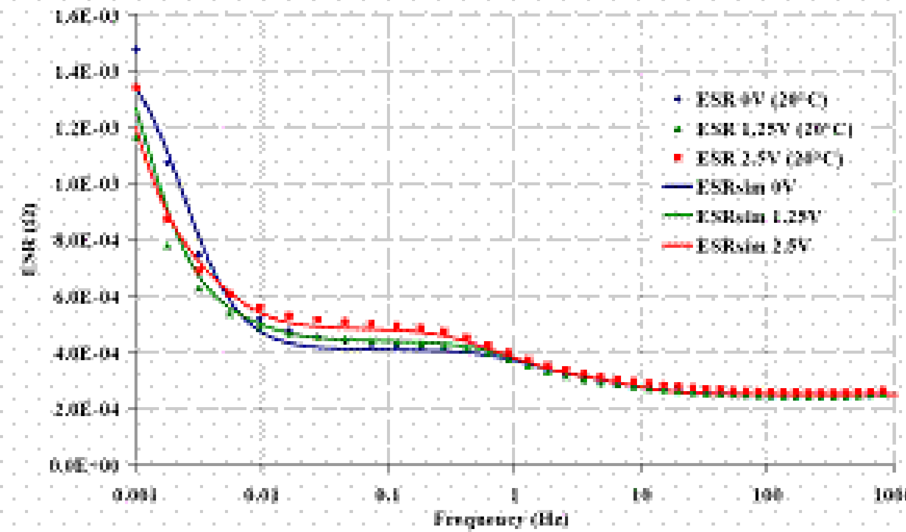


Figure 2: BCAP0010 series resistance frequency spectrum for 3 different polarization voltages.

More information on http://www.garmanage.com

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