Tecate Group
Ultracapacitor, Capacitor, Manufacturing Solutions

Tecate Group

Powerburst Presentation

APEC 2011

- **LOCATION: SAN DIEGO, CA USA**
- **INVENTORY**
- **SALES & MARKETING**
- **ENGINEERING**
- **QUALITY MANAGEMENT**

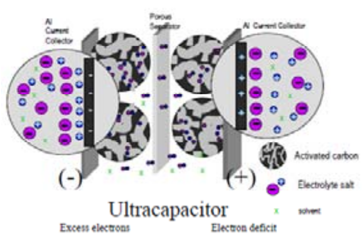
What is an Ultracapacitor?

An ultracapacitor, also known as supercapacitor or double layer capacitor, is an energy storage device which utilizes high surface area carbon to deliver much higher energy density than conventional capacitors

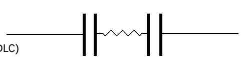
Basic Theory:
Capacitance is proportional to the surface area of the carbon, divided by the charge separation distance (C α A / d)

As area (A) ↑, and charge distance (d) ↓ capacitance (C) ↑↑↑↑

C = I * dt / dV
ESR = dV / I
Charge stored: Q = CV



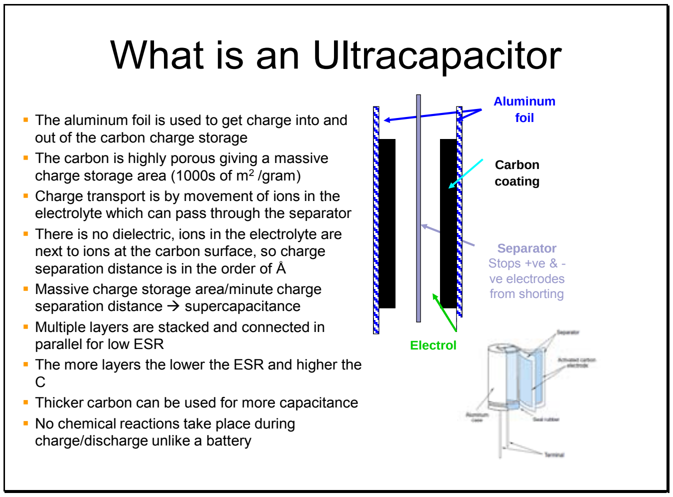
Basic Electrical Model:
Electric Double Layer Capacitor (EDLC)



Ultracapacitors are also known as supercapacitors or double layer capacitors

They store energy similar to traditional capacitors. The main difference being the high surface area achieved by using a carbon based electrode.

Since capacitance is directly proportional to surface area, this increase in surface area allows capacitance ranges up to several thousand farads.



Typical surface area for carbon is in 1000-2000 m^2/gram.

Since no dielectric is used, charge separation is in the order of angstroms.

Since no chemical reaction is taking place the life expectancy of these cells are stated in 10 years or hundreds of thousands of cycles.

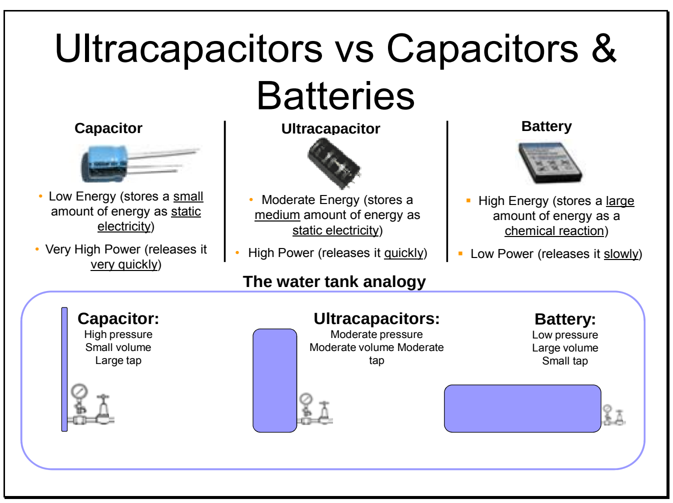
Carbon electrodes are tailor made for achieving higher capacitance or lower ESR.

Main advantage of these devices are:

- Long life
- High Power Density
- Wide Temperature Range

Current Challenge:

- Low cell voltage
- Low Energy Density
- Cost



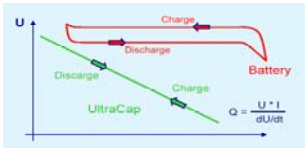
Ultracapacitors fill in a gap between traditional capacitors and batteries.

They provide a higher energy density than traditional capacitors, and higher power density compared to batteries.

With the long life capability, it provides a good solution for short-term high power applications.

Ultracapacitors vs Capacitors & Batteries

Available Performance	Lead Acid Battery	Ultracapacitor	Conventional Capacitor
Charge Time	1 to 5 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Discharge Time	0.3 to 3 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Energy (Wh/kg)	10 to 100	1 to 10	< 0.1
Cycle Life	1,000	>500,000	>500,000
Specific Power (W/kg)	<1000	<10,000	<100,000
Charge/discharge efficiency	0.7 to 0.85	0.85 to 0.98	>0.95
Operating Temperature	-20 to 100 C	-40 to 65 C	-20 to 65 C

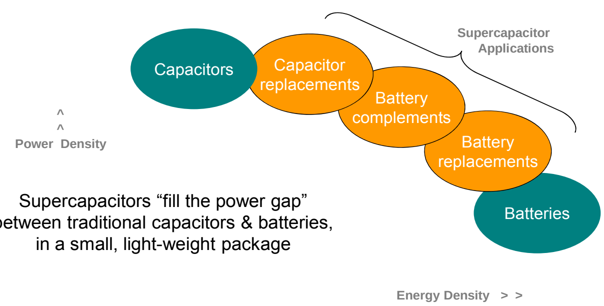


One main difference between batteries and ultracapacitors is in their discharge curve.

Batteries tend to have a flat discharge curve, whereas ultracapacitors have a linear drop in voltage as power is delivered.

Because of this difference, designers need to allow for maximum voltage swing on the ultracapacitors in order to extract the energy stored. Typically dropping the voltage by 50% will allow removing of 75% of the energy.

The Power Gap



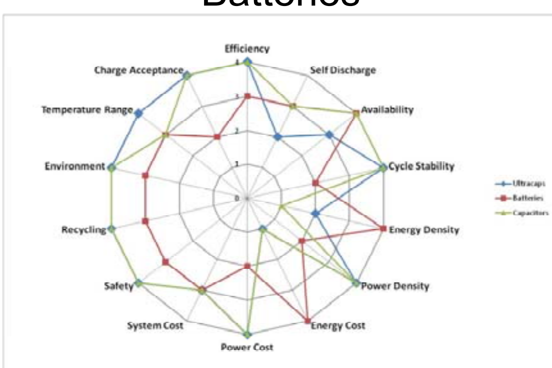
Supercapacitors "fill the power gap" between traditional capacitors & batteries, in a small, light-weight package

Even though ultracapacitors are not a direct replacement for batteries in most applications, they do fill a power gap that exists between traditional capacitors and batteries.

In some applications, they replace batteries, while in some they are used to complement batteries and allow for the use on smaller or less powerful batteries.

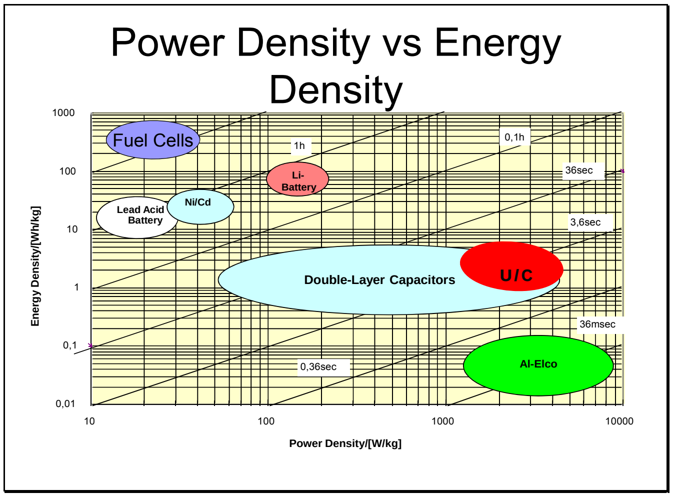
The combination of batteries with ultracapacitors has shown drastic increase in battery life in some high power application.

Ultracapacitors vs Capacitors & Batteries



As can been seen in this spider chart, ultracapacitors are strong in power density, power cost, safety, environmental, charge acceptance, efficiency and cycle stability.

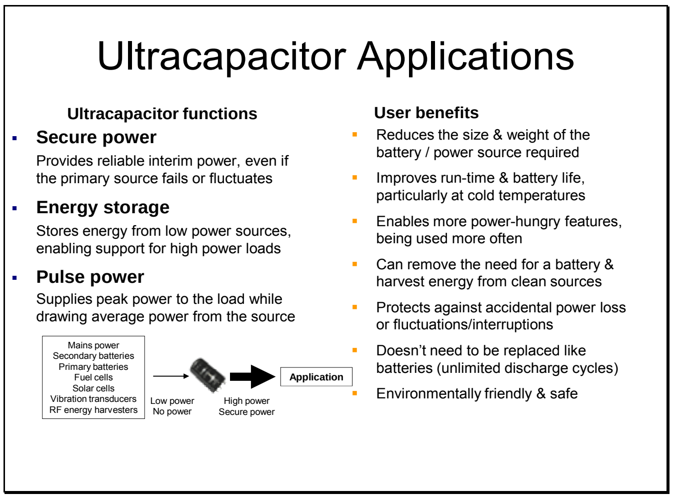
These are some typical attributes where traditionally batteries are challenged.



No energy storage solution in the market can achieve the high energy and power density combined.

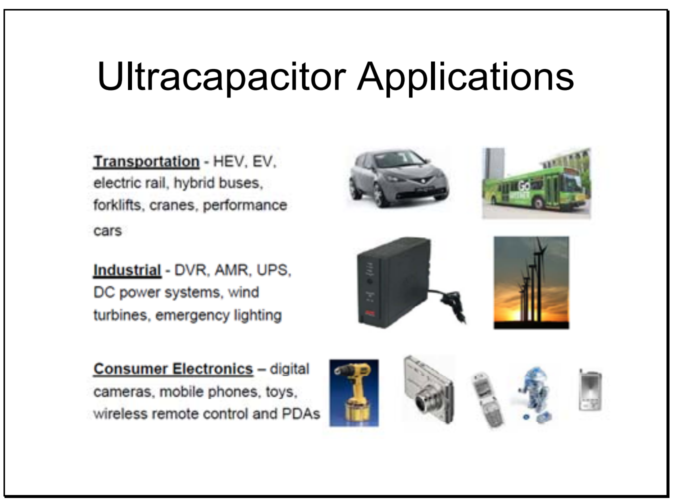
Fuel cells are one of the most energy dense solutions available. Their challenge is in quick burst power and startup time. This is why the combination of Fuel cells with ultracapacitors is very natural and provides for a perfect energy storage solution (if cost was not a factor!)

A more economical solution is the combination of lead acid batteries with ultracapacitors.



Typical applications are:

- Secure power-where immediate backup power is needed for critical applications
- Energy Storage-where energy is stored from low power medium and supported for high power loads.
- Pulse Power-used as a buffer with low power energy sources to provide peak power demands



Industries served:

- Transportation-HEV, rail, buses, truck, crane, etc. To augment main the engine to reduce high power demand and increase efficiency.
- Industrial-AMR, wind turbines, emergency lighting, etc. To act as main energy source for applications needing high reliability sources, or to augment existing low power energy sources in case of AMR.
- Consumer Electronics-digital cameras, toys, VCR, etc. To act as backup energy source or augment batteries.

Applications- AMR

Function
- Back up power in case of power failure
- Current for burst transmissions (1-2 Amps)

Advantages
- Excellent performance over wide temp. range
- High cycle count
- Long life – 10yrs
- Maintenance free
- Green vs. Batteries

Product
- PB, PBL, PBF and customs

Related
- Burst transmission. Sensors, alarms, gps…
- Dying Gasp, SSD, USB, Battery replacement

One of the most popular applications for small format UC cells is in the Automatic Meter Readers.

The cells are charged using a low power connection available and are used to supply the high power need during a transmission.

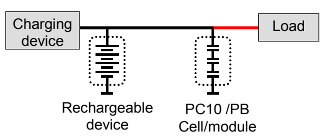
Main advantage is the long life along with temperature performance.

Applications: Access and Security

Function
- Supply power to motors and actuators during power disruption
- Supply power to alarm

Advantages
- Redundant local power
- Reduction in cabling
- Weight reduction
- Built in active or passive balancing

Product
- TPL, custom PB/PBLL Modules



In this application, the cells are used as a backup source to power an actuator or alarm in case of power outage or emergency.

Advantage is in long life, reliability, and small foot print.

Applications: UPS

Function
- Short term bridge power in case of power drop-out / glitches
- Buffering against voltage sag – high value mfg
- Graceful power down – robotics, medical, actuators
- Power for material delivery. Track with recharge.

Advantages
- Ultimate in reliability – no maintenance
- Integrated solution, replaces external UPS
- Wide temperature range
- Fast energy in case of emergency

Product
- TPLS

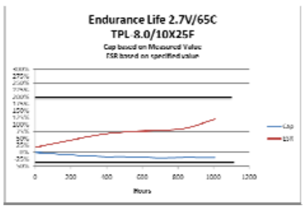
The cells are used as short-term backup solution and also a buffer against any voltage sags.

Advantage is in their ability to provide fast response to outages, extended operating temperature, and reliability.

End of Life & Failure Modes

•In general ultracapacitors do not have a hard end of life failure similar to batteries.
•Their end of life is defined as when the capacitance and/or ESR has degraded beyond the application needs.

Failure under typical use condition



Failure under Abuse Conditions

- Over voltage
  - Loss of capacitance
  - Increase of ESR
  - Bulging
  - Possible venting
- Over temperature
  - Loss of capacitance
  - Increase in ESR
  - Bulging
  - Possible venting
- Mechanical Stress
  - Deformation
  - Broken lead
  - Increase in ESR

Unlike batteries, UC do not have a hard end of life failure mode.

They show a gradual decrease in performance over its useful life.

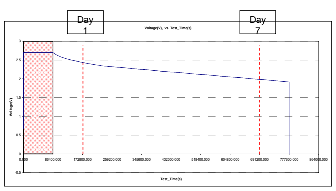
Each application will have a difference end of life criteria.

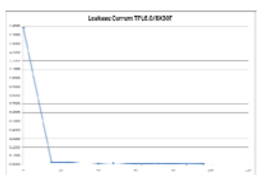
The state of health can be easily monitored within each discharge cycle.

Self Discharge & Leakage Current

Self Discharge: Is the voltage drop on a charged cell after a set period of time.

Leakage Current: Is the stable parasitic current expected when capacitor is held indefinitely on charge at the rated voltage. This value is voltage and temperature dependent.





UC cells will typically have a higher leakage current during the first 72 hours of use.

The leakage current will drop drastically and hold over the lifetime of the part.

The leakage current is voltage and temperature dependent.

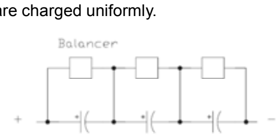
Series/Parallel Combination

Why in Series: Since ultracapacitor cells are limited to 2.7V per cell, for higher voltage application multiple cells have to placed in series.

Design considerations: When placing capacitors in series their effective capacitance is reduced by the number of cells placed in series:

$$\frac{1}{Csys} = \frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3} + \frac{1}{Cn}$$

Also when placing cells in series appropriate cell balancing needs to be added to ensure all cells are charged uniformly.



Similar to traditional capacitors UC cells can be placed is series to achieve higher voltage.

Placing cells in series will increase the voltage and reduce the effective capacitance.

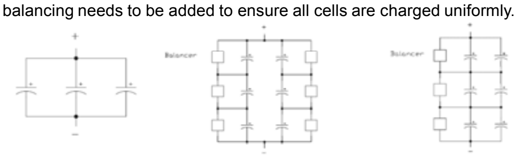
Series/Parallel Combination

Why in Parallel: Since not all capacitance values are covered by cell offered, customers can place multiple cells in parallel to achieve higher capacitance/storage.

Design considerations: When placing capacitors in parallel their effective capacitance is increased by the number of cells placed in series:

$$C_{sys}=C_1+C_2+C_3+C_n$$

Also when placing cells in series/parallel combination appropriate cell balancing needs to be added to ensure all cells are charged uniformly.



Similar to traditional capacitors, ultracapacitors can be placed in parallel to achieve higher capacitance.

By placing cells in parallel the voltage will remain the same and the effective capacitance will be increased.

Ultracapacitor Balancing

Why Cell Balancing?

- Achieve cell to cell voltage balance.
- Accounts for variations in capacitance and leakage current. Initial charge and voltage is dependent on capacitance. Sustained voltage is dependent on leakage current.
- Reduces voltage stress on an individual cell.
- Increase overall reliability of the individual cells.

Different methods of Cell Balancing:

- Passive
- Active

When cells are placed in series, they will not always share the voltage uniformly. Thus, a balancing scheme will need to be used.

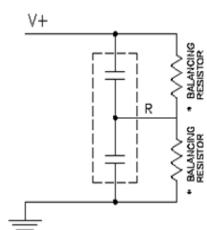
Two common methods of balancing is Active and Passive balancing.

Passive Cell Balancing

Resistor placed in parallel with each cell.

Resistor size determines balance rate.
  10x LC,slow balance,
  100x LC,faster balance.

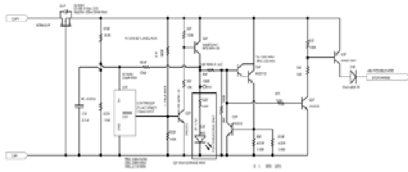
Good for low duty cycle or when stand by loss not an issue.



With passive balancing same value resistor is placed in parallel to each cell. Resistor size will depend on the cell leakage.

Active Cell Balancing

- Active circuit placed in parallel with each cell.
- Circuit will bypass current only when cell go above rated voltage.
- Ideal for high cycle applications or when stand by losses needs to me at a minimum.
- There are several different topologies available. All are more complicated and more expensive than passive balancing.



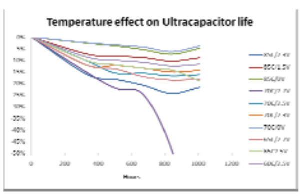
Active balancing is achieved by using a circuit to bypass current when a cell goes above its rated voltage.

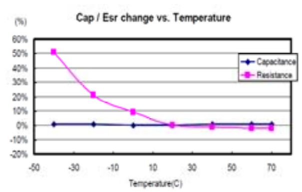
The benefit is having lower power consumption and allowing the cells to hold their charge for longer period of time.

Ultracapacitors Temperature Effect

One of the main advantages of ultracapacitors is its wide temperature range. The effect of temperature on ultracapacitor cells is two fold:

1. **Life**: Operating at high temperature extremes will reduce the life of the cells.
2. **Performance**: Operating at low temperature extremes will increase the internal resistance of the cell.





Temperature will affect cells in two ways:

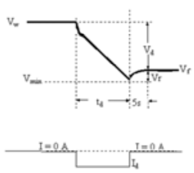
1. Life: the cell life is reduced if operated at elevated temperature.
2. Performance: Cell resistance increases at extreme low temperature.

How to Measure an Ultracapacitor

Tecate Group uses a constant current discharge method to measure capacitance and resistance on ultracapacitor cells and modules. For this method standard capacitor formulas are used as stated below:

$$C = I_d\left(\frac{\Delta T}{\Delta V}\right) \qquad ESR = \frac{Vf - V\min}{Id}$$

Where:
I_d=current (A)
C=capacitance (F)
$\Delta V = V_w - V_f$ (V)
$\Delta T = t_d$ (s)



Most common way to measure an ultracapacitor cells is using a constant current discharge and measure voltage drop versus time.

Traditional capacitors formulas can be used to calculate capacitance and ESR.

How to Size your Ultracapacitor

There are several ways to size the proper ultracapacitor for your application. The most straight way is using a constant current sizing method. For this method the following information is needed:

V_{max} : maximum voltage the application will charge to
V_{min} : minimum voltage the application will discharge to
I : the discharge current
ΔT : discharge time between V_{max} and V_{min}

using standard capacitor formulas we can calculate the capacitance needed:

$$\text{Capacitance} = I * \Delta T/(V_{max} - V_{min})$$

Note: For high current application the ESR effect will also need to be taken into consideration.

For constant power application the total energy needed can be calculated in terms of Joules (W*SEC) and the capacitance derived using the following formula:

$$E = \frac{1}{2} C(V\max^2 - V\min^2)$$

In order to size the appropriate size capacitor for an application the following information is needed:

- Max Voltage (Operating Voltage)
- Min Voltage
- Current or Power Needed
- Discharge time needed

Traditional capacitor equations can be used to calculate estimated capacitor size needed.

Sizing Example

1) Define System Requirements
   15 W delivered for 10 seconds
   10V max; 5V min
2) Determine total energy needed: J=WS=15W*10sec=150J
   a) Determine Capacitance based on: $J=1/2CV^2$
   b) Substitute the energy from above: $150J=1/2C(V_{max}^2-V_{min}^2)$
   c) Solve for C: $C=300/(10^2-5^2)=4F$
3) Add 20-40% safety margin — Csystem = 4.8F
4) Calculate number of cells in series (since maximum cell voltage = 2.5V)
   10V/2.7V = 3.7 — 4 cells in series
5) Calculate cell-level capacitance
   C = Csys * # of series cells = 4.8F* 4 = 19.2F per 2.7V "cell"
6) Choose closest cell available
   22F cell, 4 in series. — TPL-22/12X35F

Tecate Tools

- Website: www.tecategroup.com
  - Application notes, White Papers, etc.
- Sizing Tool- All UC solutions
- PowerBurst Product Guide
  - Overview with detailed design considerations