

# Electrical Energy Storage to Meet Evolving Aircraft Needs

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## Abstract

The value of “ultracapacitors” (also referred to as “supercapacitors” or “electric double layer capacitors” in some literature) as an augmentation device when placed in parallel with “electrochemical” energy storage (i.e. battery) is presented in this paper. Since ultracapacitors possess unique attributes due to their higher value of energy storage density (or Joules/WattHrs per mass) compared to conventional capacitors while maintaining the peak power providing capability (to some degree) typical of conventional capacitors they may provide a near term solution in applications demanding longer battery operating life when placed in parallel. Such demands may be pronounced by the onset of More-Electric-Aircraft peak loads and “cold-crank” Auxiliary Power Unit (APU) electric-starting in demanding cold temperature environments.

The potential benefits of an ultracapacitor in parallel with a battery will be illustrated through a very simple lab demonstration as well as a more complex system consisting of a large motor inrush load (cold-cranking condition) through the use of a computer simulation tool (Simulink). In addition to the ultracapacitor discussions and demonstration, other forms of advanced energy storage will be reviewed for their potential near or long term application in meeting the evolving needs of More Electric Aircraft as presented at the 2011 International Double Layer Capacitor and Hybrid Energy Storage Seminar in Deerfield Beach Florida (Reference 3).

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## SYSTEM CONSIDERATIONS AND DISCUSSION

In applications where large transient electrical loading demands are placed on electrochemical batteries traditionally used in military vehicles such as modern aircraft, ground vehicles and other platforms, batteries experience a high degree of induced stress. Specifically, the stress a battery might experience is pronounced under conditions where vehicles may be operating under extreme temperature conditions, such as providing “cold-cranking” power to a starter motor at the onset of startup. Since electrochemical batteries store and deliver power involving chemical reactions (versus “electrostatically” as in the case of capacitors) a tremendous amount of internal heating with electrode material expansion and contraction results throughout a complete charge/discharge cycle (Reference 1).

As the chemically based constraints are coupled with the higher resistance associated with the liquid based battery electrolytes (with resistance inversely proportional to temperature), a high induced stress mechanism is established. Experience in the field has indeed shown that battery maintenance intervals (and potential battery replacement) on

the order of 120 day cycles are possible for military aircraft and perhaps even shorter for high end use commercial airliners. In cases where a minimum voltage must be maintained to a starter motor, a battery system may also need to be oversized (more cells in series) to meet voltage capability requirements and/or oversized to handle the peak power required. Batteries alone may not be optimum to meet these requirements and are inefficient in terms of peak power delivery.

Figure 1 to the right and below illustrates concepts involving various forms of energy storage utilization in system design. The inrush current demands of the C-5 Modernization Auxiliary Power Unit (APU) Starter Motor is also provided in Figure 2 below. The data is representative of a worst-case starting condition at -40 deg C and illustrates the peak levels instantaneous current can reach with an exponential type decay to obtain torque to the starter motor.

## ADVANCED SYSTEM CONSIDERATIONS

In addition to the potential system applications involving electric-start assist, other advanced applications for future



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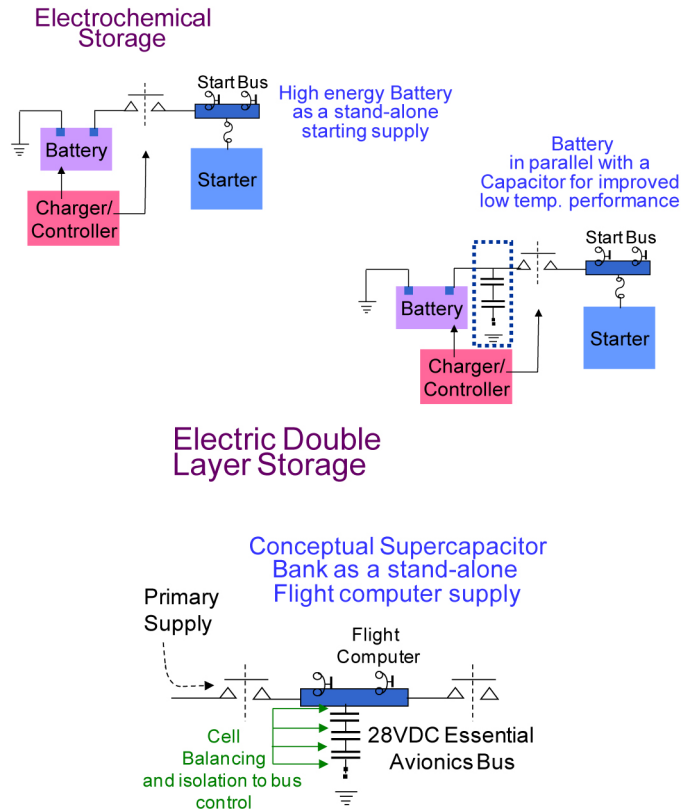
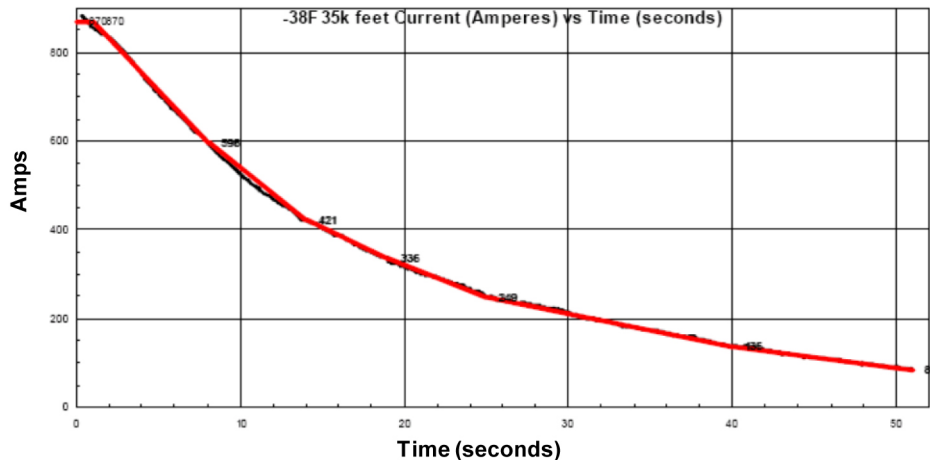


Figure 1. Energy Storage Throughout the Applications



... 3 of these attempts allowed in a 5 minute period

Figure 2. C-5 APU Electric-Start Load

aircraft may include needs for a tremendous amount of peak power to support rapid turn-on weapons where typical generator response time may be inadequate. Figure 3 below provides a hypothetical power profile for such a weapon. Other applications may involve the ability to “sink” large amounts of “back-emf” (or regenerative energy, i.e. “regen”), and potentially use the “regen” as a recharge source to optimize overall vehicle efficiency. A comparison to such

issues being explored and matured in the hybrid vehicle industry is provided in Figure 4.

**• More Electric Vehicle challenges are not unlike those of the Hybrid Vehicle industry**

- High levels of regenerative energy during vehicle braking parallels flight control motor braking although ...

- Energy levels differ



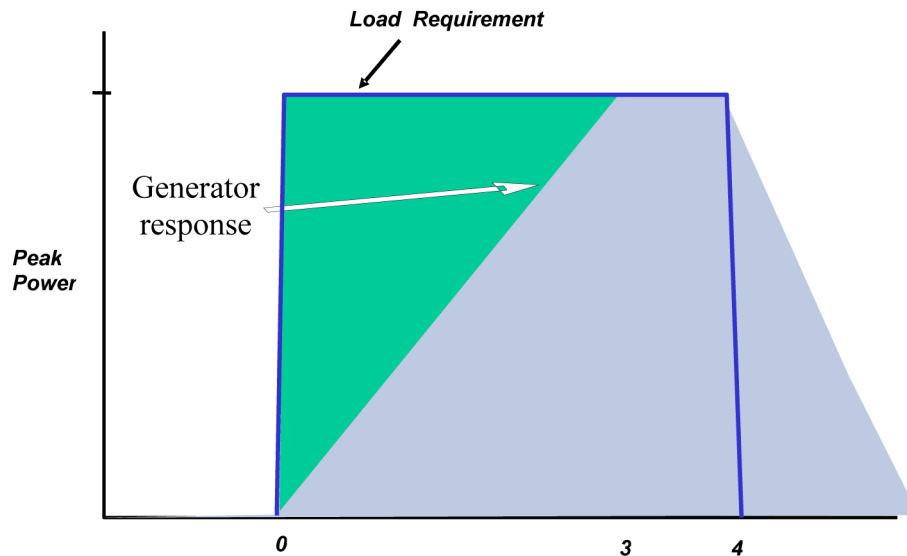


Figure 3. Weapon Rapid Turn-on Profile

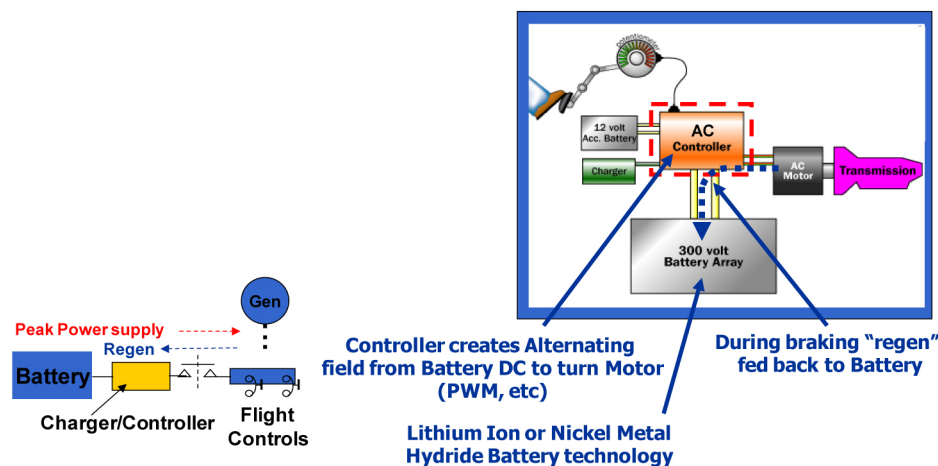


Figure 4. Hybrid Vehicle Parallels (graphic taken from Hybrid Vehicle website)

- Recaptured energy allows Hybrid Vehicle to propel without Internal Combustion Engine
- Hybrid and More Electric Aircraft architectures are driving specific energy and power density improvements of energy storage components

In summary, many of the key aspects that are researched in any energy storage technology for evolving or existing applications can be summarized as follows:

- High energy density (kJoules per pound and per in<sup>3</sup>)
- High peak power density (kWatts per pound and per in<sup>3</sup>)
- Safety (no hazardous material "outgassing" on overcharge)
- Charge/discharge efficiency (minimal loss between charge/discharge as waste heat)
- Regenerative energy absorption (ability to absorb regen without degradation, outgassing, etc)

- Packaging robustness (does the packaging approach optimize peak power performance, minimize voids and maintain thermal integrity)
- Aircraft environment (survive thermal, vibration, humidity)
- Technology maturity (can the technology be readily fielded if required or are there significant technology hurdles)
- Could the technology be a "game changer"

## CAPACITOR BACKGROUND

With an overview of the system needs for energy storage established, both applied to evolving and existing retrofit vehicles, it is appropriate to review the foundational equations governing energy storage and how this is applied to the revolutionary approaches being undertaken by the various developers in the field.

The equation governing the amount of stored energy that can be achieved in any capacitor technology (or

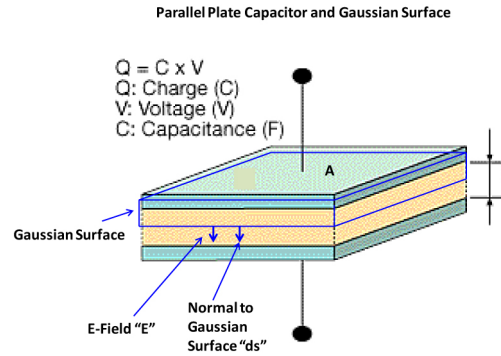


**Figure 5. Parallel Plate Capacitor**

“electrostatic” device) is as follows (with  $U$ =stored energy,  $V$ =Capacitor Breakdown Voltage and  $C$ =Capacitance):

$$U = \frac{1}{2} C V^2 \quad (1)$$

Where:

$$C = \epsilon A / d \quad (2)$$

With:  $A$ =Area of the capacitor plates

$d$ =distance between the capacitor plates

$\epsilon$  = relative permittivity of the dielectric  $\epsilon_r$   
x permittivity of free space  $\epsilon_0$

In [equation \(1\)](#) above, the expression for stored energy has been derived from the work performed to establish the Electric Field “E” across the parallel plate structure shown in [Figure 5](#). Work, defined as the total to assemble stored charges, can be written in the integral form for distributed charges as follows:

$$U = \frac{1}{2} \int \rho_v V dv \quad (3)$$

Using relations:  $\rho_v = \nabla \cdot \mathbf{D}$  and  $E = -\nabla V$  and theorems from vector calculus, it can finally be shown that:

$$U = \frac{1}{2} \int \epsilon E^2 dv = \frac{1}{2} \epsilon E^2 A d = \frac{1}{2} \epsilon V^2 A / d = \frac{1}{2} C V^2 \quad (4)$$

In [equation \(2\)](#) above, the expression for basic capacitance  $C=Q/V$  is combined from Gauss's Law:

$$Q = \epsilon E A \quad (5)$$

with the Electric Field defined as normal to the Gaussian surface of a parallel plate with  $ds$  (differential surface area element) also normal to the same surface (dot product or cosine of angle between the two =1)

$$V = E d \quad (6)$$

as defined from the definition of electric potential

[Figure 5](#) below defines the Gaussian surface (in blue) across a conventional parallel plate structure used to derive [equation \(5\)](#) and [\(6\)](#) and the Electric Field “E” to establish [Equation \(4\)](#) above.

From [equations \(1\)](#) and [\(2\)](#) it can be seen that to maximize the amount of stored energy (also proportional to capacitance) “A” must increase while “d” must decrease. This is the essential element of ultracapacitor design where an extremely small separation distance “d” (at the atomic level) is achieved with highly porous carbon electrodes to achieve high “A” as compared to traditional capacitors.

[Figure 6](#) below provides a typical cross-sectional view of an ultracapacitor where the basic electric double layer structure separating the positive and negative charges in principle corresponds to the parallel plate structure shown in the figure above.

Other capacitor innovations involve increasing  $V$  to impact a higher stored energy “U” although, as will be shown in the “Technology Comparison” Section below, with less success.

A summary of the discussion above with relevant relationships is provided in [Figure 7](#) below.

## TECHNOLOGY COMPARISONS

While no one technology may simultaneously meet many of the desired characteristics for a given application, certain technologies when reviewed on a case by case basis for a given application can certainly be considered more optimum than others and may meet a high percentage of the desired characteristics (robustness, efficiency, etc).

When selecting a technology, as has been pointed out in energy storage conferences and related electrochemical capacitor papers ([References 3](#) and [6](#)), energy and peak power density terms should be considered highly dependent on rate of charge/discharge and temperature. Therefore, in referring to these “density” terms and the general values published from vendors, attention is required. Technologies driven by achieving higher “V” (as mentioned in the previous section) do tend to achieve much higher power density since instantaneous power is dominated by  $P=I*V$  (current \* voltage). As was shown in the presentation by Dr John Miller

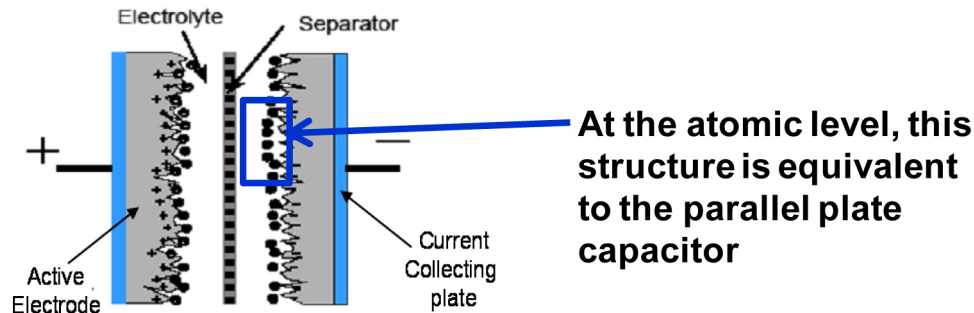


Figure 6. Electric Double Layer Capacitor Structure (Reference 5)

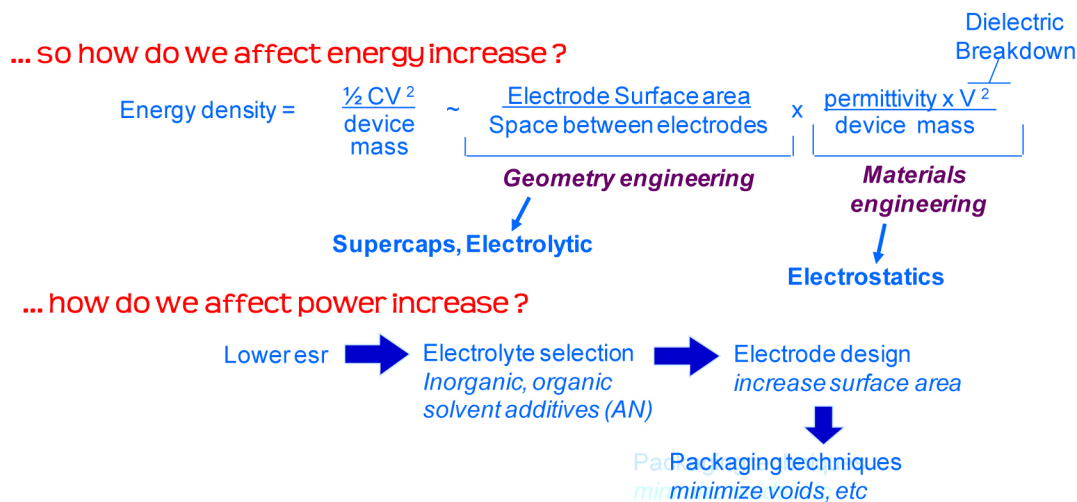


Figure 7. Energy and Power Relationships

specifically (reference 6) and others, calculating peak power density for any technology does require attention to the particular method used (i.e. “matched load” response) and is influenced by several factors including temperature and efficiency at charge/discharge power levels as mentioned above.

Given the above considerations, the “Ragone” chart below provides some general published power and energy densities for various technologies studied in a side by side comparison. Where peak power and high voltage storage is required, ceramic capacitors, film capacitors, hybrid tantalums and other material development technologies seeking improved breakdown voltage (as given in [equation \(4\)](#)) may be optimal. Conversely, a higher level of energy storage for lower voltage applications may be optimally derived from electric double layer capacitors (or supercapacitors). Finally, higher energy with less peak power needed can be obtained from battery (electrochemical) storage although, as shown in the expanded view in [Figure 9](#) some battery technologies appear to be successfully expanding peak power capability. Fuel Cells (if they are indeed considered a form of “energy storage”), which rely on a continuous fuel supply (an oxidant), can achieve very high

levels of energy density as the supply is continuous with chemical energy turned into electrical energy.

Far less mature technology studies are seeking orders of magnitude increases in both peak power and energy such as Magnetic Capacitors and Metal-Air Batteries.

[Table 1](#) below provides another comparative breakdown among capacitor technologies and includes frequency and temperature capability as an additional attribute for comparison. In general, due to the larger time constant associated with “shuttling” charges across the porous structure of ultracapacitors, their time constant and thus associated frequency response is poorer. Also, most capacitors are limited in temperature capability by either their: a) associated grown oxide material (in the case of electrolytic and hybrid tantalums), b) thermal fatigue characteristics (in the case of a ceramic capacitor surface board mounted design) or c) liquid based electrolyte (in the case of the ultracapacitor technology). In general, it can also be stated any capacitor utilizing a grown oxide as it's dielectric medium is limited in temperature capability due to oxide leakage at elevated temperature. Many of these comparisons came with input from capacitor developers (reference Acknowledgements section).