Capacitors and Aircraft Power System Considerations for Higher Temperature Operation and Wide Bandgap Enablement

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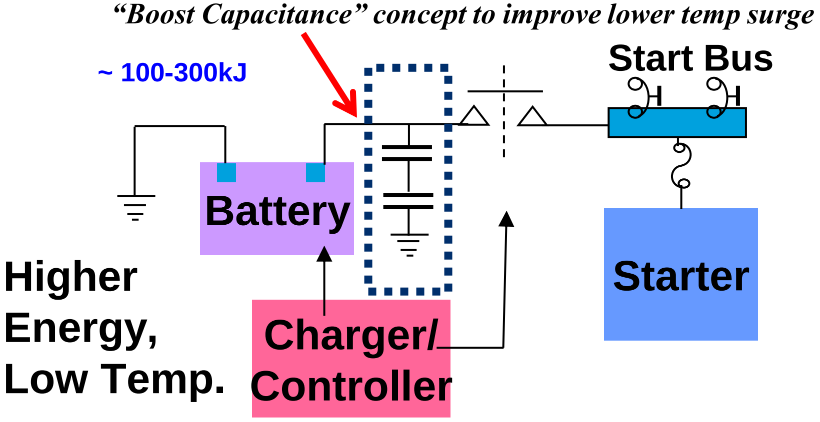
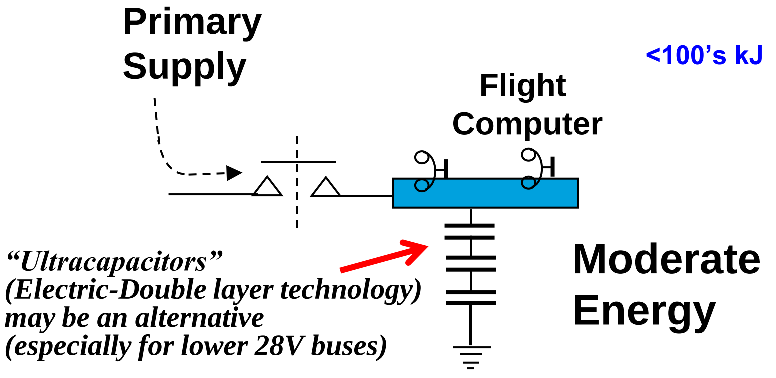
How is Energy Storage Used in Aircraft?

a) Electric (APU)-Start Supply



- Commonly met by Electrochemical (Batteries) Storage

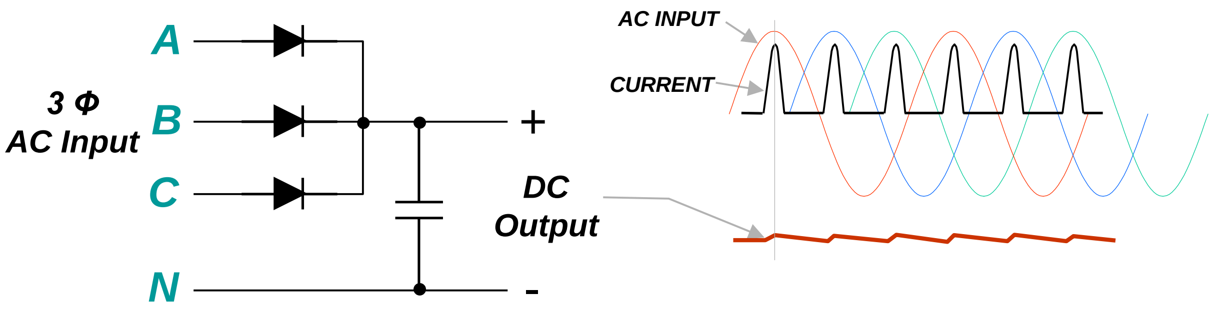
b) Momentary Power fill-in to Avionics



- Commonly met by Electrochemical (Batteries) Storage (which may provide dual use as a Start-Supply)

Low Energy, High Temp.

c) AC-DC Prime Power Output Filtering



- Commonly met by Film Capacitors

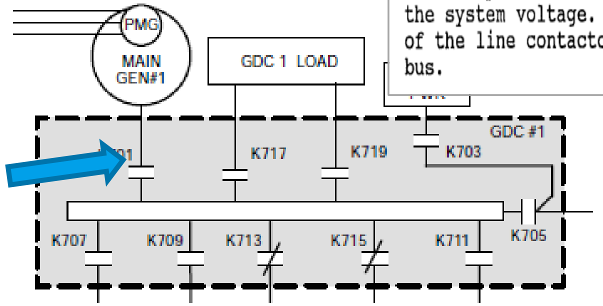
MIL-STD-704 Power Quality at the Aircraft Bus

Steady state characteristics	Limits
Steady state voltage	108.0 to 118.0 volts, rms
Voltage unbalance	3.0 volts, rms maximum
Voltage modulation	2.5 volts, rms maximum
Voltage phase difference	116° to 124°
Distortion factor	0.05 maximum
Distortion spectrum	Figure 3
Crest factor	1.31 to 1.51
DC component	+0.10 to -0.10 volts
Steady state frequency	393 to 407 Hz
Frequency modulation	4 Hz
Transient characteristics	**Limits**
Peak voltage	271.8 volts, rms maximum
Voltage transient	Figure 4
Frequency transient	Figure 5

Defined at the Aircraft Power Bus "point of regulation" (por)

3.18 Point of regulation. The point of regulation (POR) is that point at which a power source senses and regulates the system voltage. The POR shall be at the input terminals of the line contactor connecting the power system to the load bus.

por



Influences Power Supply design interfacing with the Aircraft Power Bus

Steady state characteristics	Limits: 28 volts DC system	Limits: 270 volts DC system
Steady state voltage	22.0 to 29.0 volts	250.0 to 280.0 volts
Distortion factor	0.035 maximum	0.015 maximum
Distortion spectrum	Figure 8	Figure 13
Ripple amplitude	1.5 volts maximum	6.0 volts maximum
Transient characteristics	**Limits: 28 volt DC system**	**Limits: 270 volts DC system**
Voltage transient	Figure 9	Figure 10

Information compiled from Reference 1

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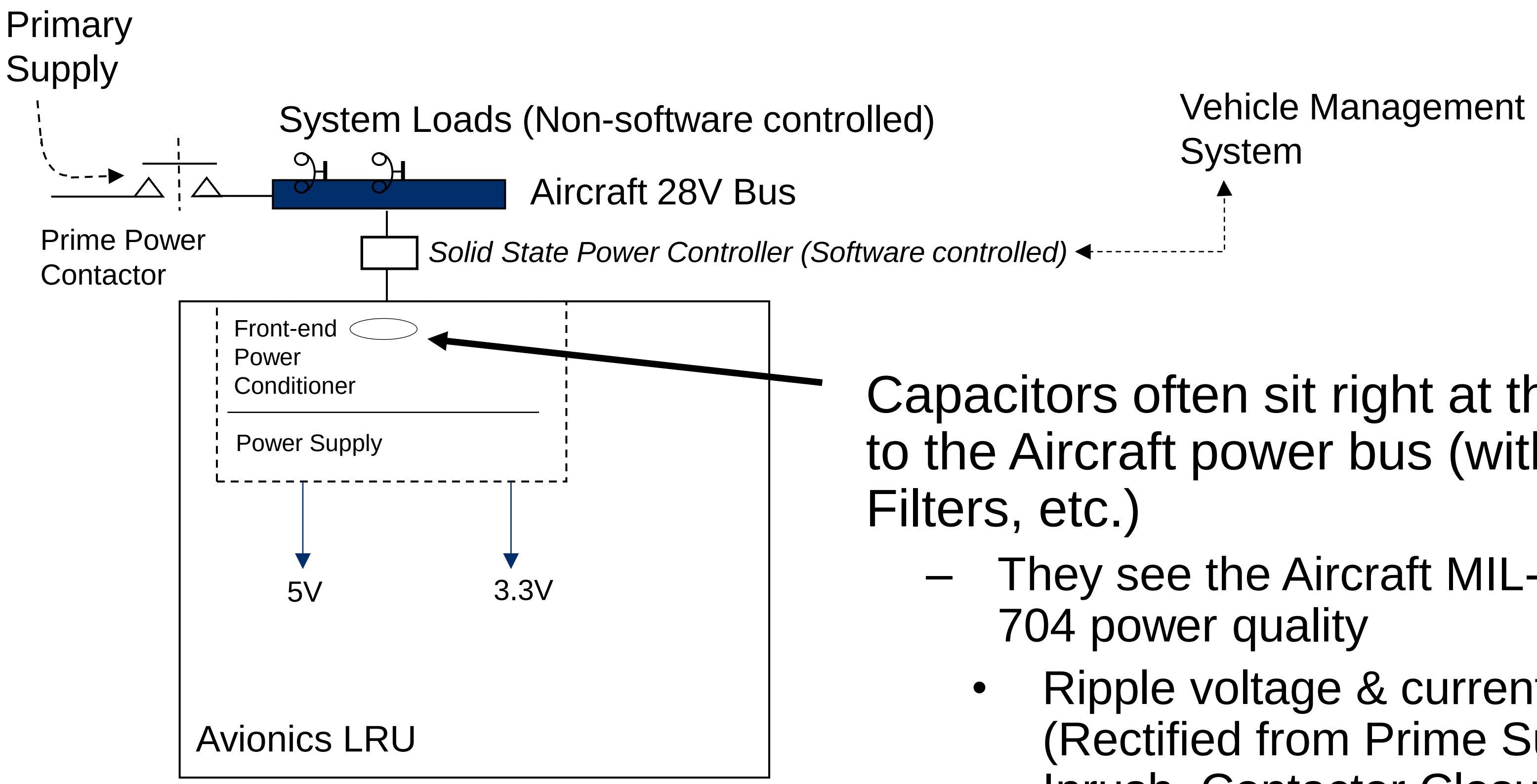
Capacitor front-end interface to the Aircraft Bus



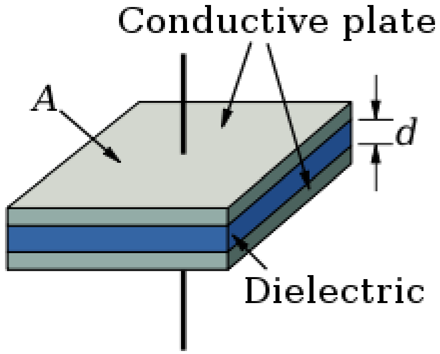
Capacitors often sit right at the input to the Aircraft power bus (within Filters, etc.)

- They see the Aircraft MIL-STD-704 power quality
  - Ripple voltage & current (Rectified from Prime Supply)
  - Inrush, Contactor Closure induced transients
  - Abnormal Aircraft Operating Mode induced transients (and at temp. extremes for the Box)

You mean I need to design my box for all the extreme corner conditions! But the Capacitors can get so large!

Capacitor Basics - Parameters that drive Capacitance

- Now that we have briefly examined Energy Storage applications in Aircraft, let's look at more of the fundamentals
  - Capacitors store charge across plates separated by an insulator (or dielectric) vs. "electrochemically" (as in the case of Batteries)
  - There are many varieties of Capacitors based on the type of dielectric and how it is formed (& how the electrodes are made)



$C = \varepsilon \cdot (A / d)$

Where:

ε = **permittivity** of dielectric

A = Area of the plates

d = distance between the plates

Breaking down **permittivity** further …

$\varepsilon = \varepsilon_r \varepsilon_0$

Relative permittivity of the Dielectric ← ε_r

ε_0 → Electric constant ~ 8.854 x 10^{-12} F/m

Graphic compiled from Reference 2

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Achieving High Capacitance (Energy Storage)

How do we effect an Energy increase through the various attributes?

Maxwell's Equation Brings in the additional Dielectric Breakdown term

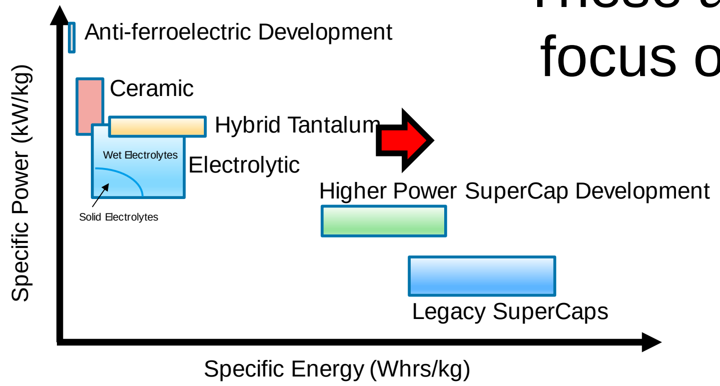
Dielectric Breakdown

$$\text{Energy density} = \frac{\frac{1}{2} CV^2}{\text{device mass}} \sim \frac{\text{Electrode Surface area}}{\text{Space between electrodes}} \times \frac{\text{permittivity} \times V^2}{\text{device mass}}$$

Geometry engineering

Materials engineering

These are the areas developers focus on to boost performance

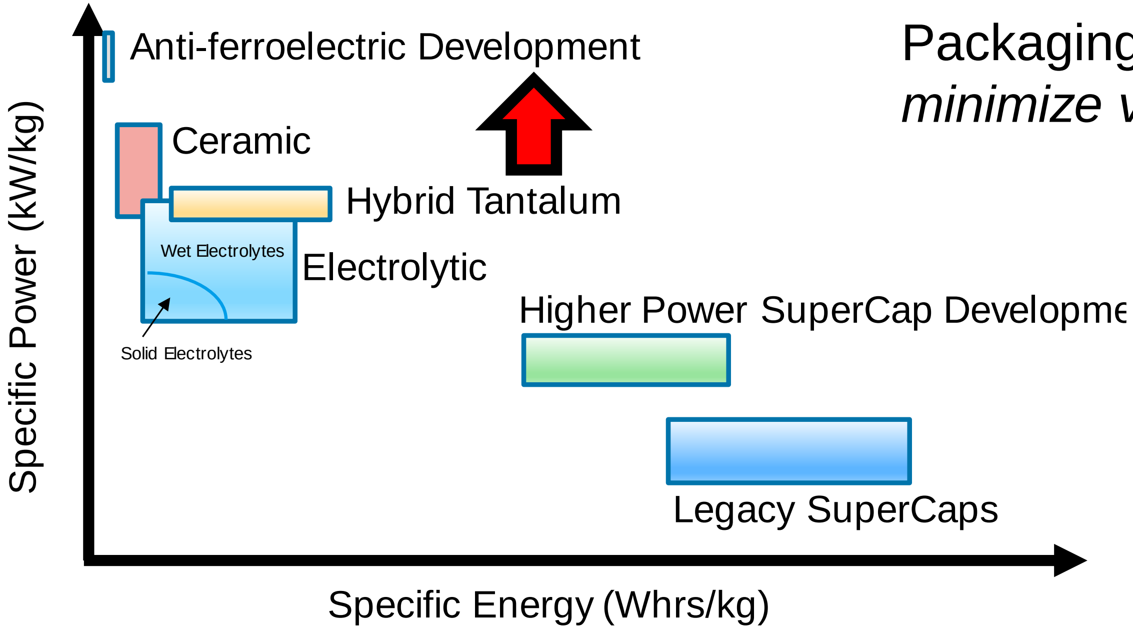


Specific Energy = (V x I x t)/mass
Specific Power = (V x I)/mass

Achieving High Power in Capacitors

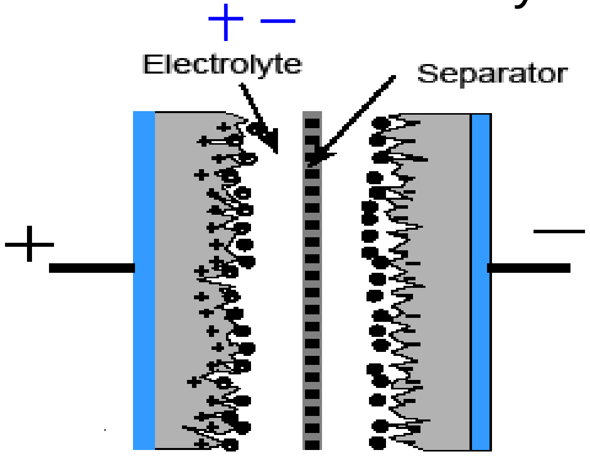
Applies to Electrochemical and Electrolytic Caps

Lower esr → **Electrolyte selection**
Inorganic, organic
solvent additives (AN)
→ **Electrode design**
increase surface area
→ **Packaging techniques**
minimize voids, etc



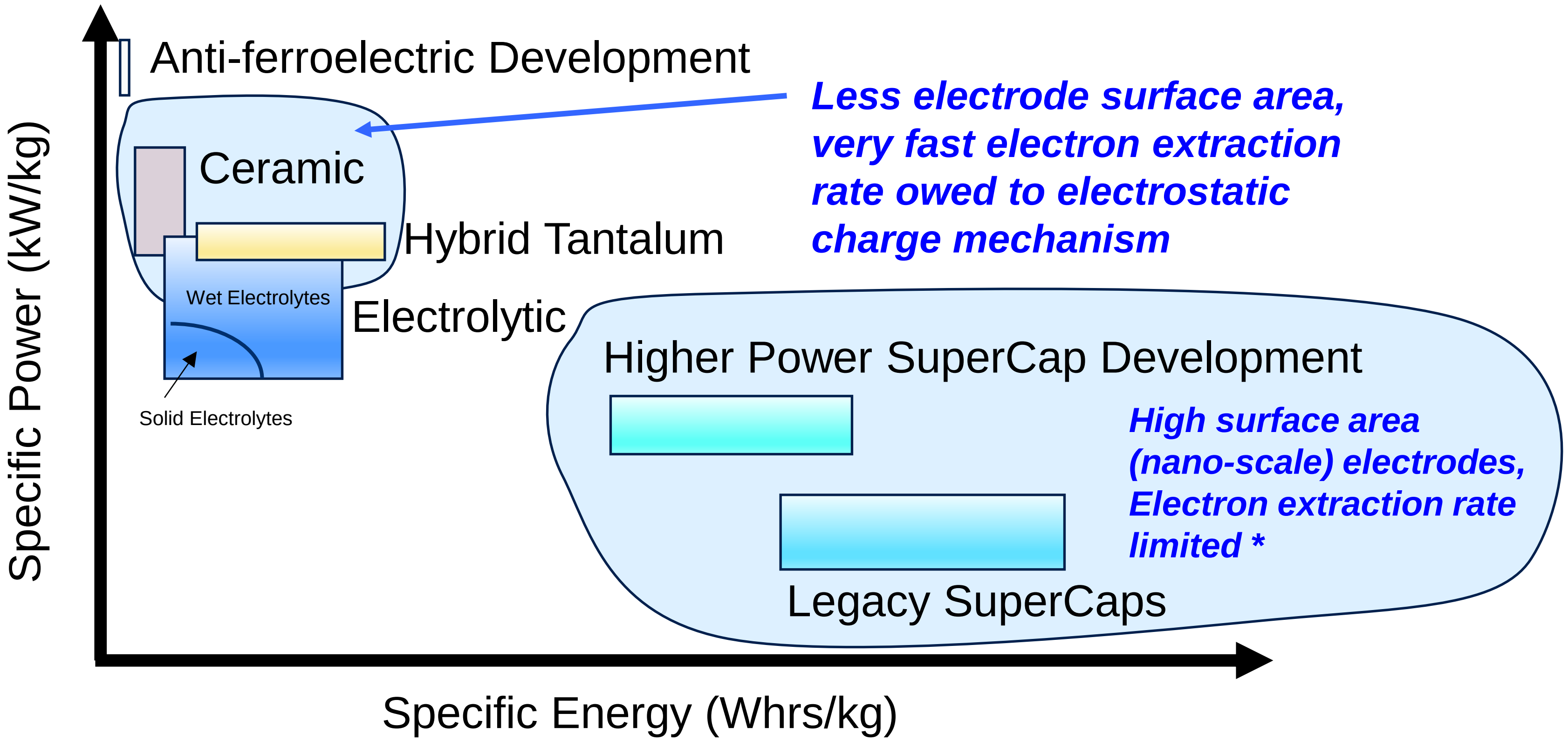
Specific Energy = (V x I x t)/mass
Specific Power = (V x I)/mass

Polarized electrolyte



Graphic from Reference 4

Capacitor Comparisons - Energy & Power ("Ragone")



Specific Energy = (V x I x t)/mass
Specific Power = (V x I)/mass

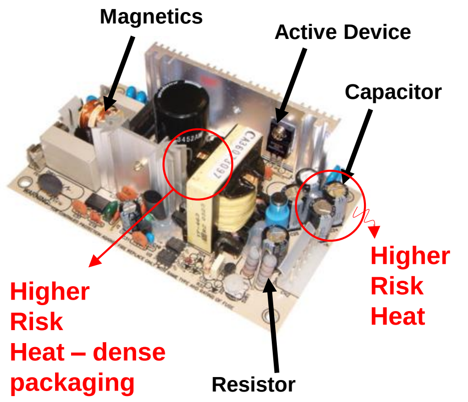
** Think of moving embedded electrons out of small pockets*

Capacitor Development needed for Higher Temperatures & WBG Support

- Temperature capability of Active Devices is climbing through Wide Band Gap Materials advances
  - Processors, Advanced Engine Controls, Power Switches
    - 200 deg. C and beyond

Capacitor Technologies	(Typical) Upper Operating Temp Limit (˚C)*	Temperature Limiting Factors/Comments*
Traditional Ceramic (High Temp variants)	125 (250)	Non uniform heating for large geometries, insulation resistance drops above the Currie point of the dielectric. Failure to closely follow soldering restrictions. Failure to properly layout PCBs for fragile large geometry parts.
Aluminum Electrolytic	150	Electrolyte, voltage derating implications vs. temp.
High Temp Tantalum	230	Traditional tantalums limited by electrolyte and packaging. Surface mount Tantalums are not surviving heat/voltage as well as leaded devices. Attachment and constraint of large leaded devices.
Traditional Power Supply Film (polyethylene, polyphenylene)	110	Limitations in the film material (as plastic transition temperature is approached insulation properties lost). The films are severely limited with toxic polysulfide as the best. Bulk/weight causes end tab mechanical connection failures.
Ultracapacitor Module (Electric Double Layer)	65	Electrolyte. High ESR means high losses and excess internal heating.

Typical Power Supply



Graphic and information from internet web search on power supplies

*Temperatures and Comments represent a range available from typical devices based on web search and supplier sites

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Design Considerations for Using Capacitors

- Inrush must be managed
  - Pre-charge any capacitor bank to mitigate large start-up transients on the system prior to the actual need
- Manage large strings of capacitor cells
  - Passive, active power electronics cell balancing
- Traditional Electrochemical Supercaps are low voltage per cell (~ 2.3V per cell depending on electrolyte type)
  - Weight impact, # of cells in series to meet a high voltage bus (270V) needs to be examined closely
- High ripple content? Improvements via WBG based power supplies but higher risk due to internal capacitor heating?

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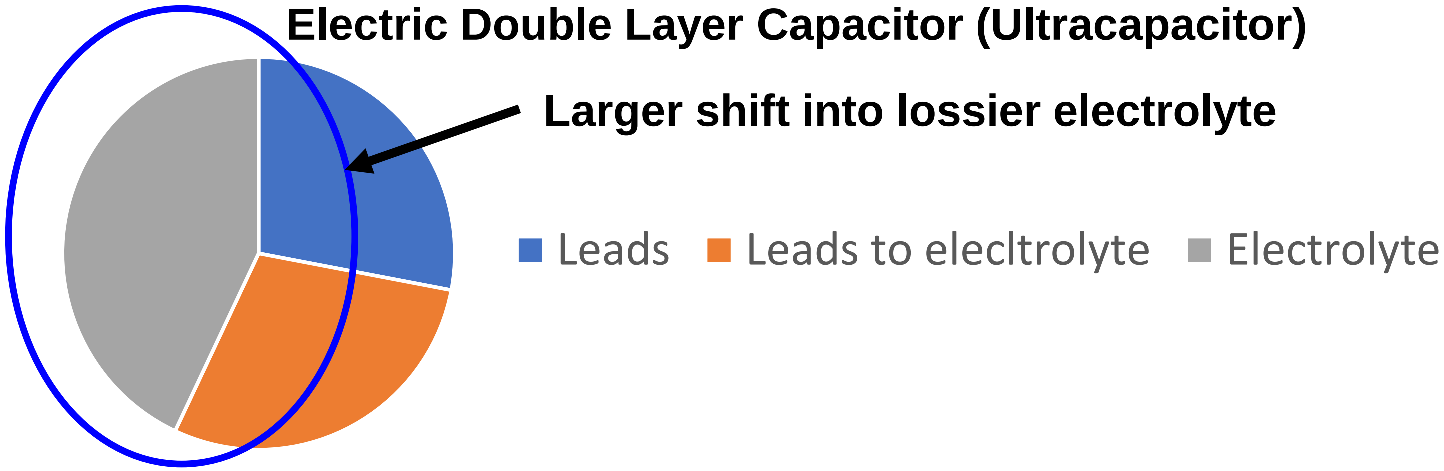
Heat Dissipation % by component for Capacitor Types

Rough estimates requiring further validation



Larger % heating in electrolyte shifts utility away from adopting Electric Double Layer Capacitors in WBG-based high ripple filtering applications

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Conclusions

- Capacitor and Energy Storage advancements are taking on a variety of interesting forms and developments for More-Electric
  - There is not a “one size fits all” solution
- Mechanical, Electrical and Environment can all induce stress on Capacitor devices
- Are Capacitors keeping pace with the developments in Wide Band Gap Switching and Higher Temperatures/Op. Frequencies?
  - Heating due to high ripple current conditions in More-Electric?
  - High voltage - High Farad Supercap type technology?
    - Safety aspects need to be considered for Aircraft installations (e.g. safety shorts across terminals)

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References

1. MIL-STD-704 Aircraft Electric Power Characteristics, Revision E, 1 May 1991, Table I & II
2. Wikipedia web site searches, Electrolytic Capacitors
   https://en.wikipedia.org/wiki/Electrolytic_capacitor
3. VISHAY Introduction to Wet Electrolyte Tantalum Capacitors, Document Number: 40021 Revision 01-Sep-03, pg 4 (http://www.vishay.com/docs/40021/wtintro.pdf)
4. Maxwell Technologies Product Guide 1.1

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