



Aluminum Electrolytic Capacitors in Power Electronics

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Aluminum electrolytic capacitors are available in an enormous range of case styles and sizes.



The highest volume type is the V-Chips in both polymer and liquid electrolyte types. It is not specific to power electronics. Surface mount V-Chip styles and solid polymer chip style aluminum electrolytic capacitors are more than a third of the North American aluminum electrolytic market.



Radial leaded types are the dominant output capacitor type in board power supplies because of lowest cost. They are connected in parallel as needed to achieve the required capacitance and ESR. They are available in 85 °C and 105 °C types from many suppliers



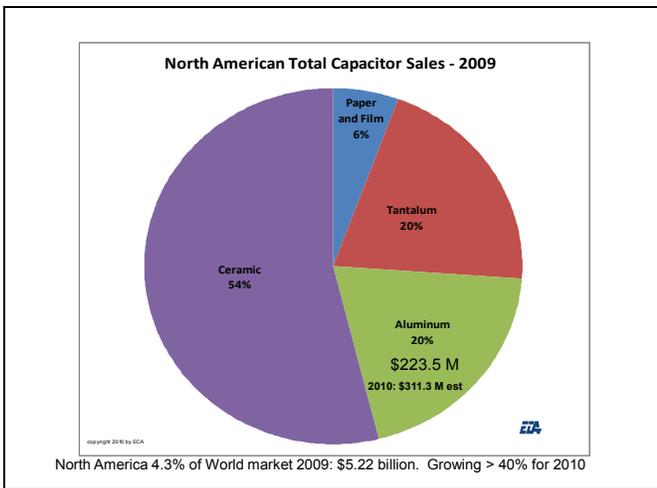
Snap-in types are the preeminent input capacitor in board power supplies, and are popular for their standardization. Over the last 10 years, the capacitance per can has more than doubled. The standard 10-millimeter pitch leads allowed makers to introduce new smaller size series and switch their customers to them with no need for a change in customer production tooling.



Screw terminal capacitors are popular as inverter dc-link capacitors, and are available up to 700 V and can diameters up to 4 inches.



The CDE Type MLP aluminum case flatpack capacitors and the MLS stainless steel case capacitors are specialty niche capacitors included here because of their outstanding performance. The half inch high box shape and long-life TIG weld seal makes it the square peg capacitor for the square holes in power electronics. Similar capacitors are available as type CUBISIC LP made by SIC-SAFECO in France.



Aluminum electrolytic capacitors are 20% of the 1½ billion dollar North American market for capacitors, and aluminum electrolytic sales are up about 40% over 2009, an admittedly bad year. The North American consumption of aluminum electrolytic capacitors is only 4.3% of the world market.

Aluminum Electrolytic Strengths

- Wide voltage range, 5–700 V
- High capacitance, up to 3 farads
- High energy density, 1.5 J/g or 2 J/cm³
- Low cost for high capacitance
- Typical > 10 years life

Aluminum electrolytic capacitors are the favorites for more-is-better applications. Their affordable high capacitance and wide voltage range makes them the choice for power electronics.

Aluminum Electrolytic Weaknesses

- Loose cap tolerance, $\pm 20\%$ typical
- Limited high frequency, < 100 kHz
- Limited current handling from high DF
- Perceived as less reliable due to wear out and explosion failures.

However, they have limited use in instrumentation because of loose tolerance and limited high frequency capability. Generally, can't be used in AC applications because of high dissipation factor. And even though their self-healing characteristic actually gives them expected lifetimes that are as good or better than other types, the fact that they wear out and can fail by exploding feeds the perception that they are less reliable.

ESR



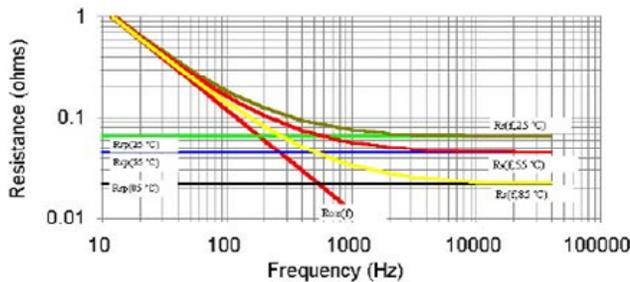
- ESR is the equivalent series resistance
- It is a lumped-parameter component
- It is one resistor that would dissipate the same amount of power as the capacitor is dissipating
- This pretend resistor is in series with the capacitor
- ESR increases at cold temperatures and below about 10 kHz
- Ripple current flow thru the ESR heats the capacitor and shortens its life.

You get a free, and generally unwanted, resistor with each aluminum electrolytic capacitor called ESR. ESR is an important characteristic for aluminum electrolytic capacitors because compared to other capacitor types it is high and it determines expected lifetime in applications with a lot of ripple current.

ESR Components

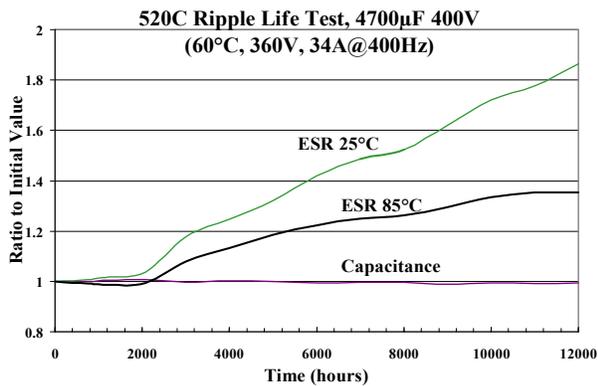
$ESR = R_{ox} + R_{sp}$

ESR Components
 $R_s = R_{sp} + R_{ox}$ vs f & T



ESR decreases with increasing frequency and temperature. At low frequencies, like less than 5 kHz, ESR is determined by the oxide resistance, the DF of the aluminum oxide dielectric. At higher frequencies the oxide resistance drops out and the ESR is mostly the electrolyte resistance which increases 10 to 100 times at cold temperatures.

ESR Change in Ripple-Life Test



In rectification filter applications the current in the capacitor—the ripple current—flows through the ESR, heats the capacitor and shortens life. However, actual capacitors do better than expected because the hot ESR increases much less than the 25 °C room temperature ESR that is measured after test. Here in this example, while the 25 °C ESR increased 90 % in 12,000 hours, the hot ESR only increased 35% (12,000 hours is 1.4 years).

Compared to Ceramic & Tantalum

- Ceramic, MLCCs and disks
 - Max capacitance is 220 µF but growing
 - Good for AC and high frequency
 - Cracking a problem in large chips
- Tantalum, Solid
 - Max voltage 50 V and polarized
 - Short circuit failures and catch fire
 - Reliable because they do not wear out
 - Polymer tantalum not flammable

By comparison, ceramic and tantalum capacitors are generally thru-hole board mount and surface mount types. Multilayer ceramic capacitors, MLCCs, are mostly SMT types with limited capacitance. High voltage and high frequency types compare to our mica capacitors. They are more reliable than aluminum electrolytic capacitors except in the large chips that crack in temperature cycling and assembly.

Solid tantalum capacitors are, like aluminum electrolytics, polarized and don't work with AC voltage. They are available up to 1000 µF and up to 50 V. In low source resistance applications like input capacitors in power supplies they can fail short circuit and burst into flames. The newer, more expensive polymer tantalum capacitors, in which the MnO₂ cathode is replaced with conductive polymer, don't catch fire and have lower ESR. A strength of solid tantalum capacitors is that they don't wearout. There is no known wearout mechanism; they get more reliable the longer you use them.

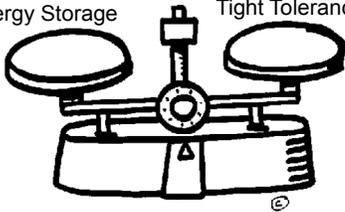
Compared to Film Capacitors

Electrolytic Strengths

High Capacitance
High Energy Storage

Polypropylene Strengths

High Voltage, AC Voltage
Tight Tolerance



In dc link applications, the high capacitance and energy storage of electrolytics give them a big advantage when ride through time is needed for power outages. Bus voltages over 450 V are an advantage for film because the capacitors do not need to be connected in series.

Compared to Film Capacitors

- Metallized polypropylene capacitors excel in high voltage, AC voltage and tight tolerance.
- Aluminum electrolytics excel in capacitance and energy storage.
- Large metallized polypropylene caps are growingly popular in green applications, e.g. Wind Turbines, Solar Converters, and Hybrid / Electric Vehicles

Capacitance is much more expensive in metallized polypropylene film capacitors but are popular in AC applications and green applications.

Aluminum Electrolytic Applications

- General circuit applications
 - Audio coupling
 - Photoflash and strobe flash
- Power Electronics applications
 - Input capacitors
 - Output capacitors
 - Inverter dc-link
 - Motor drive bus
 - Welders

Aluminum electrolytic capacitors excel in more-is-better applications: applications in which more capacitance works better and there is little need for tight tolerance capacitance, temperature stability, or high frequency performance. Cornell Dubilier is focused on the power electronics applications because they need the larger types in which CDE specializes. Recent fast market growth has been in wind turbine inverters.

DC-Link Capacitors

- DC-Link is fastest growing, >30 % CAGR.
- Energy storage and voltage smoothing after power rectification in inverter applications.
- DC-link capacitors are of two types
 - Metallized polypropylene film
 - Aluminum Electrolytic
- Here's how they compare

DC link is the spot in the power electronics after the rectifier at the input to the voltage regulator. The high energy density of the aluminum electrolytic capacitor makes it the high-value choice. The market is growing greater than 30% per year. The battle is on for the power film capacitor to take market share. Here's how aluminum electrolytic and metallized polypropylene power film capacitors compare.

DC Link Capacitor Ripple Current Handling

- DF of alumina 60x polypropylene, so
- Aluminum electrolytics heat more < 5 kHz
- Same size film and lytics have about same heating at high frequency

The dissipation factor of anodic alumina is 60 times higher than polypropylene, causing electrolytics to heat more at lower frequency than film capacitors. At higher frequencies, the heating is dominated by the ohmic (non-dielectric) losses and may be similar for film and lytics of similar size, depending upon construction details.

Energy and Amperes Cost

For rectified 440 Vac bus capacitors, the typical costs are:

	Per Joule	Per Amp
Polypropylene Film	20–50¢	\$1
Aluminum Electrolytic	5–10¢	\$3

Most aluminum electrolytic applications use more capacitance than necessary, and many film applications use more ripple capability than needed. This is due to design requirements, the intrinsic relationship between stored energy and ESR of the capacitor dielectric, the thermal conductivity, and economic constraints. Power film is a third the cost for ripple current but is five times the cost on energy storage.

Assembly and System Costs

- Film caps are simpler and no resistors
- Series lytics, > 500 V bus, need resistors
- Results in more complex bus structure
- Lytics can explode, collateral damage.
- Film smaller and lighter for same current, lytics smaller and lighter for same energy.
- Film caps generally produce less heat.

Assembly time of multiple capacitors and resistors is simpler for film capacitors because you don't need to insulate cans or use sharing resistors or heatsink.

Aluminum caps need voltage-sharing resistors for series-capacitor banks. Electrolytics need to be connected in series and generally require voltage balancing resistors.

Cost of more complex bus structure for series designs. Electrolytics need more elaborate and costly bus work.

Failure mode and collateral damage—Electrolytics may cause additional damage when they fail.

Total size and weight of capacitor versus bank—Films are smaller and lighter for a given amount of ripple handling at low ambient temperatures, while electrolytics are smaller and lighter for a given energy storage

Power dissipation of capacitor—Films generally produce less heating

Comparative Performance 1

- Lytics have 7–10 times the **capacitance**↑
- Lytics higher **ripple current** at 85 °C↑
- But lytics have 10x or more **ESR**↓
- Lytics have about the same **ESL**↔
- Films better withstand **overvoltage**↑
- Films better at **low temperature**↑.

Besides \$/J and \$/A, other performance considerations are:

Capacitance—Electrolytics offer much higher capacitance per volume and price.

ESR and ESL—Films have lower specific ESR; very similar series inductance.

Ripple Current Handling—Though films have lower specific ESR, the voltage withstanding capability of polypropylene dielectric is more severely limited at temperatures above 85 °C than is the electrolytic dielectric. This can lead to an electrolytic being able to handle more high-frequency ripple current at 85 °C than a film capacitor of the same size.

Resistance to **overvoltage surges**—Films are much better for handling overvoltage transients.

Low temperature impedance—Films are much better for maintaining low impedance below 0 °C.

While it usually works out that lytics have 10x or more ESR than power film capacitors, it is not necessarily so. At low frequencies, the dielectric DF of lytics, which is 60x that of films, holds the ESR up, but the metal resistance of large film capacitors can actually make their ESR higher than a lytic of comparable physical size. Aspect ratio matters: For lytics more foil and bigger diameter or length lowers the ESR, but for film capacitors, while a larger diameter makes the ESR lower, a taller winding makes the metallic ESR higher. So, hockey-puck shaped film capacitors have lower ESR, but hockey puck shape doesn't help lytics.

Comparative Performance 2

- Shape—Films can be prismatic, box shape
- Films fail gracefully
- Films peak current capability same as lytics
- Expected lifetime about the same
- Reliability too is similar

Film caps can be boxes but lytics are cylinders—Form Factor available for Films are more readily offered in prismatic shapes

Failure Mode—Films generally have a graceful, more benign failure mode. Lytics can explode in large banks driven by low source impedance.

Peak current capability—Very similar capabilities; generally not an issue

Life—Very similar life capabilities but driven by economics. Design cost is reduced until barely meets the life requirement.

Reliability—Very similar reliability

Design Example 1 2000 μ F, 900 V, 100 A

- Lytics
 - Voltage requires **two 500 Vdc lytics in series**
 - Current requires **four large lytics in parallel**
 - Probably requires **voltage sharing resistors**
 - **Example:** 8x 5200 μ F 500 V, 3½x5%, \$800
- Film
 - Current requires 2 large films in parallel
 - Capacitance requires **3 large films in parallel**
 - **Example:** 3x 800 μ F 1000 V, \$240
 - Barely meets minimum cap but has 2x the current

Here is the first of two design examples. If the application requires 2000 μ F in a 900 V bus with 100 amps of ripple current, two 500 V aluminum electrolytic capacitors would be connected in series to handle the 900 V and four sets of the two in series would connect in parallel to handle the current. If eight 5200 μ F, 500 V capacitors were used, the capacitor cost would be about \$800. In addition, there would be additional cost for voltage sharing resistors.

If power film capacitors were used only two in parallel would be needed to handle the current, but a third capacitor would be needed to get the capacitance up to 2000 μ F. The three 800 μ F 1000 V capacitors would cost about \$240, and barely meet the needed capacitance.

So, for this example, power film capacitors are a third the price of aluminum electrolytics.

Design Example 2 5000 μ F, 900 V, 100 A

- Lytics
 - Voltage requires **two 500 Vdc lytics in series**
 - Current requires **four large lytics in parallel**
 - Probably requires voltage sharing resistors
 - **Example:** 8x 5200 μ F 500 V, 3½x5%, \$800
- Film
 - Current requires 2 large films in parallel
 - Capacitance requires **6 or 7 large films in parallel**
 - **Example:** 7x 800 μ F 1000 V, \$560
 - Barely meets minimum cap but has 5x the current

In this second example, the required capacitance has more than doubled. The original eight aluminum electrolytic capacitors still provide enough capacitance; so, it is the same solution as for the first example. However, four more power film capacitors are needed to make the 5000 μ F.

The power film solution is still less expensive and has five times the needed current handling capability, but barely enough capacitance.

These examples favor film capacitors as less expensive. However that is unusual, and in most applications the need for more capacitance dominates, and it's lytics that are lower cost.

Which is Best?

- Choose by required capacitance and ripple current
- Compare cost of film versus lytics including bus work and resistors
- Consider other issues
 - Required life and reliability (MTBF)
 - Cold impedance
 - Physical size
 - Overvoltage transients

The main determining factors in choosing between aluminum electrolytic and a film capacitors are usually the minimum capacitance and ripple current ratings you need.

Compare the cost of a film capacitor to meet the minimum capacitance to the cost of electrolytics (including bus work and resistors) to meet the minimum ripple current.

Next, look at other design considerations such as life, reliability, cold impedance, physical size, possibility of overvoltage transients, and the like.

Large Aluminum Types

- Screw terminal
- Snap-in
- Plug-in
- Flatpack

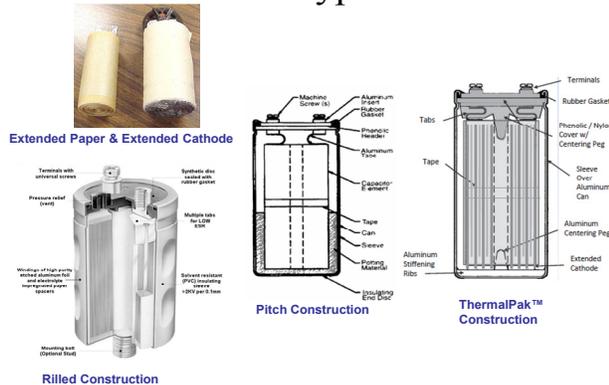
DC-Link applications need the large values of capacitance that are available in these package styles. CDE's largest volume is in screw terminal capacitors and then snap-in capacitors. Plug-in capacitors are electrically similar to the screw terminal capacitors but with different headers. They have copper plug-in pins, more capacitance per can size, and are only available in can sizes up to 2 by 5%. Our MLP and MLS flatpack capacitors are long life and a 1/2 inch tall. We also offer small radial leaded and axial leaded capacitors, but the volume is small because printed circuit assembly is mostly in the Far East.

Screw-terminal Types



Screw terminal capacitors are available with optional mounting studs and a variety of terminals in sizes up to 4 inches in diameter by 10 inches long.

Screw-terminal Types



Over much of the history of screw terminal aluminum electrolytic capacitors the standard construction was the pitch construction shown in the center. It had the disadvantage that should the capacitors be mounted sideways, horizontally, the tar could melt, block the safety vent and allow the capacitor to explode. By comparison, the superior constructions available are Rilled and ThermalPak. Both have extended cathode as shown in the top left. With extended cathode the solid metal-to-metal connection between the capacitor element and the can bottom assures that the element isn't hotter than the can. This keeps the capacitor cool and extends its life.

The Snap-in Capacitors



With terminals formed to snap-in to the board during assembly the ubiquitous snap-in capacitor is popular. It is low cost because it is highly automated and it allows upgrading because all sizes have 10 mm pitch leads. Except, larger sizes have 4 or 5 terminals for added mechanical strength and reverse-proof mounting.

Plug-in Almost Screw Terminals

- Alternate construction – 3 copper pins and standoffs replace screw terminals
- With 3 1/8 inch standoffs
- Up to 2300 μ F, 500 V



Plug-in construction variation from screw terminal capacitors is available for printed circuit mounting. The compact construction allows up to 50% more capacitance but is only available in can sizes up to 2 inch diameter by 5 3/4 inches tall.

Flatpack Capacitors



Flatpack capacitors are available with more CV than the ubiquitous 35 mm by 50 mm snap-in. They offer up to 25 joules of energy storage and are widely used for power hold up modules. They are the square peg capacitor for the square holes in power electronics.

Type MLP, Flatpack Capacitor



Less than 1/2 inch tall
 20 joules of energy storage
 Easy to stack into modules
 Easy to heatsink
 Great at cold to -55 °C

- Welded seal, flat capacitor can replace multiple snap-ins in high ripple apps
- New, 450 V. Now available 7.5 to 450 V
- Double the ripple capability with a heatsink
- 50-year life with nearly hermetic seal
- MLS with stainless case, 100 year life

The MLP is easy to stack into high-capacitance modules for power hold up. It's easy to heatsink and double the ripple current capability. 250 volt and lower voltage ratings operate to -55 degrees C. The welded seal delivers 50 year life and Type MLS with a stainless case delivers 100 years of life and 60% higher ripple current capability.

Benefits of Flatpack Capacitors

- High capacitance density in 12.5 mm pitch
- Efficient stackable form factor
- Heatsinking is simple and effective
- Extremely long life due to near-hermetic seal and high-purity materials
- Superior low-temperature impedance



The flat prismatic package delivers these benefits: high capacitance density, imminently stackable, easy to heatsink, long life, and for the 250 V and lower voltage ratings operation to -55 °C.

High Capacitance Density

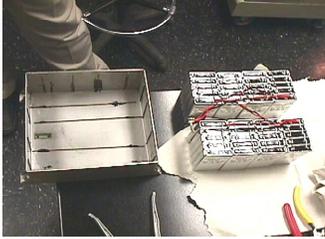
- Over twice the energy density of 35 mm 105 °C screw-terminal capacitors
- About quadruple the energy density of bank of 1/2" diameter 105 °C capacitors
- Rectangular package amplifies this performance by $4/\pi = +27\%$



The box shape fills the square-peg holes in power electronics.

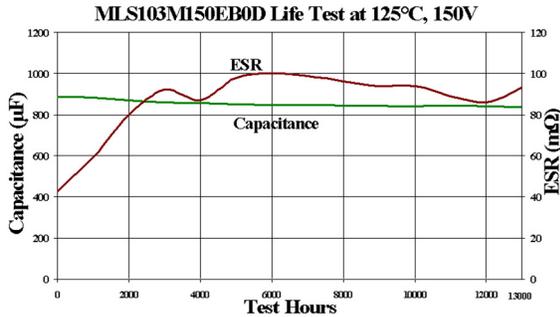
Efficient Stacking

40 MLPs being stacked for a power hold up module for the F16 fighter



A good example of the easy ability of MLPs and MLSs to be stacked into modules is this power hold up module for the F16 Fighter Aircraft. The final box assembly is solder sealed.

13,000 Hours at 125 °C Equivalent To 95 Years at 65 °C



While the Type MLS is rated to withstand a load life test of 10,000 hours at 85 °C with ripple current that would cause the core temperature to be 125 °C, here is an actual life test for 13,000 hours at 125 °C. The ESR has stopped increasing and the capacitance is not changing. It looks like it is good for many thousands of more hours. Based on expected life doubling for each 10 °C that you lower the temperature, 13 thousand hours at 125 °C demonstrates an expected life of 95 years at 65 °C. That supports the MLS datasheet claim of 100 years expected life.

A few of the MLS/MLP Avionic Applications

- KC135 Raytheon
- F18 Allied Signal
- F22 Allied Signal
- X33 Space Shuttle, Allied Signal
- JSF Joint Strike Fighter
- C17 Litton
- F18 Litton
- F16 Loral
- E2C E Systems
- Osprey V22



As you see from this list, MLPs and MLSs are popular in avionic applications.

Highlights of MLP/MLS

- High capacitance density in 12.5 mm pitch
- Efficient stackable form factor
- Heatsinking is simple and effective
- Extremely long life due to near-hermetic seal and high-purity materials
- Superior low-temperature impedance

And so in summary, they've got, high capacitance density, efficient stackability, easy heatsinking, very long life, and wide temperature capability.

Aluminum Electrolytic Capacitors Highlights

- 20% of North American capacitor market.
- <5 % of world capacitor market and >1/3 are surface mount types
- Popular large can types are snap-in, screw terminal and plug in. Flatpacks longest life
- Lowest cost capacitance type above 50 V
- Same reliability as polymer film capacitors
- Widely used as rectifier filter, dc-link capacitors in power electronics

In conclusion, aluminum electrolytic capacitors are a growingly popular type especially for rectifier filters and high capacitance. They are holding their own against the new large power film capacitors.