Capacitor Technology

Ron Demcko
Sr. Fellow – KYOCERA AVX
Ron.Demcko@kyocera-avx.com
919-271-0047

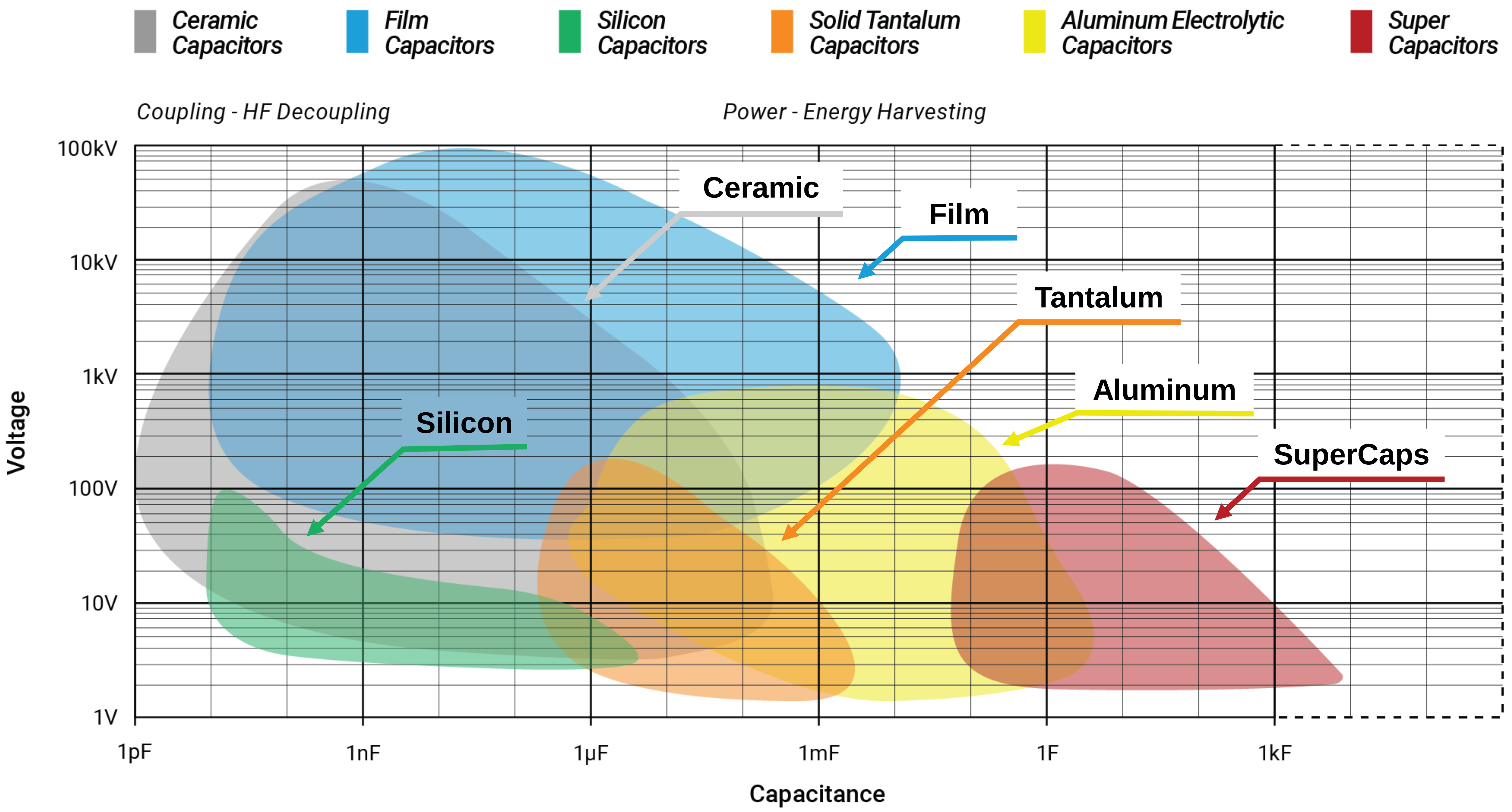
Modules

- Ceramic
- MLCCs
- Stacked
- Chip Film
- Wound Film
- Thin Film
- SuperCaps
- Aluminum Electrolytic

Goal: Understanding each capacitor technology

1. Construction
2. Performance characteristics are discussed relative to:
   - Time
   - Temperature
   - Voltage
   - Frequency
3. Reliability
4. Selection guide
5. Derating methods
6. Simulation links

Capacitors Today



Capacitor Types Technologies

MLCC

Film

Thin Film

MLO

Mica

Low - Medium Cap / Voltage
Small Case

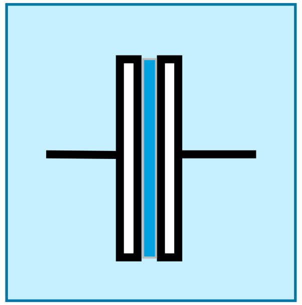
High CV MLCC

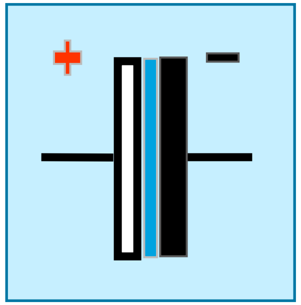
Large Cap / Voltage
Small Case

Non-Polar components:
Electrode
Dielectric
Electrode

Electrostatic Capacitors

Electrolytic Capacitors





Tantalum Chip

Tantalum Polymer

Niobium Oxide Chip

Tantalum Leaded

Al Solid

Large Cap / Voltage
Small Case

Solid Electrolytics

Tantalum Wet

Al Wet / Hybrid

High Cap / Voltage large case

Wet Electrolytics

Polar components:
Anode
Dielectric
Cathode

SMT V Chip ALUMINUM ELECTROLYTIC

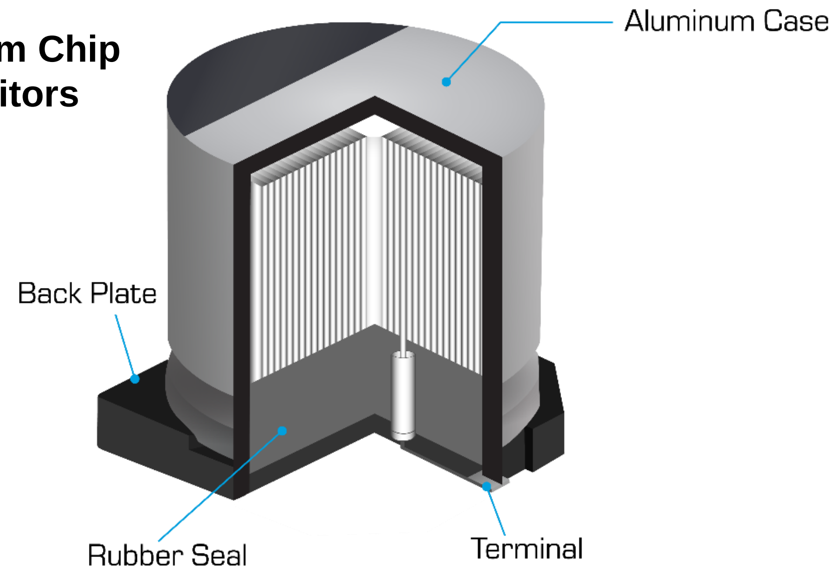
Typical high volume SMT V chips come in three technologies
Generalized ranges shown

Aluminum Electrolytic
6.3V – 400V
2.2µF – 6800µF
-55°C to 125°C

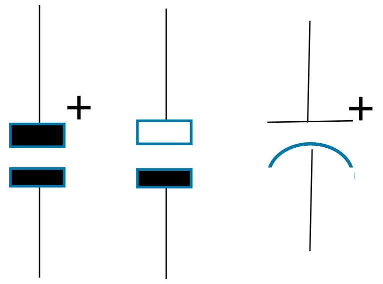
Hybrid Polymer
16V – 125V
10µF – 560µF
-55°C to 125°C

Conductive Polymer
35V – 100V
12µF – 470µF
-55°C to 105°C

Aluminum Chip Capacitors



Aluminum Electrolytic Capacitor

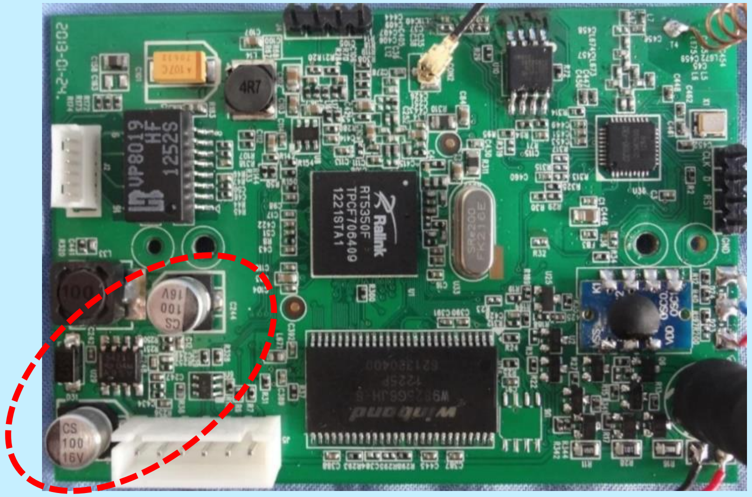


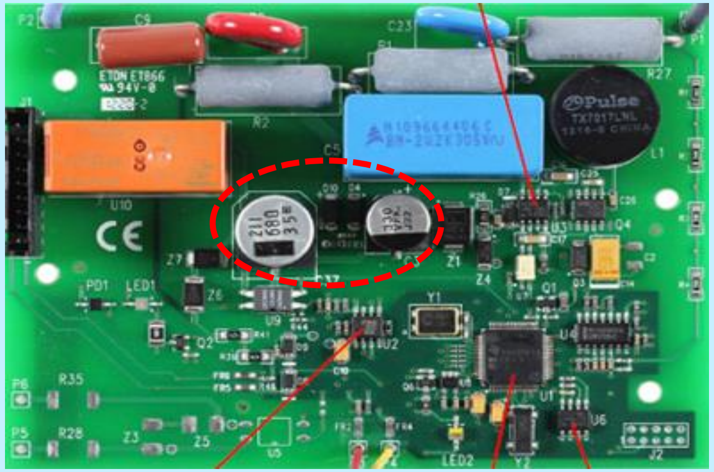
- Polarized Bulk Capacitors
- Commonly used in low frequency applications
- Ideal for high ripple loads, bulk filtering & peak power use
- Wide voltage range 6.3V to 400V
- “Generally” Stable
- Acceptable reliability with correct selection & sizing

Electrolyte	Anode Electrode Material	Dielectric	Relative Permittivity	Overall Properties
Wet / Solid	**Al - Aluminum**	Al_2O_3	~ 9.3	General Purpose, Large Value, Large RMS
Wet / Solid	Ta - Tantalum	Ta_2O_5	~ 26	High Performance, Small Size, High Reliability
Solid	NbO – Niobium Oxide	Nb_2O_5	~40	Small size, intermediate to low to mid power

Aluminum Electrolytic Technology Comparison

Attribute	Wet	Polymer	Hybrid
Benefits	•Low Cost •Low DCL •Broad Value Range	•Ultra Low ESR •Higher Ripple •Enhanced Life	•Low ESR •Low DCL •Higher Reliability
Points to Check	•Reliability •ESR	•Higher DCL •Higher Cost	•Higher Cost •Range Limits

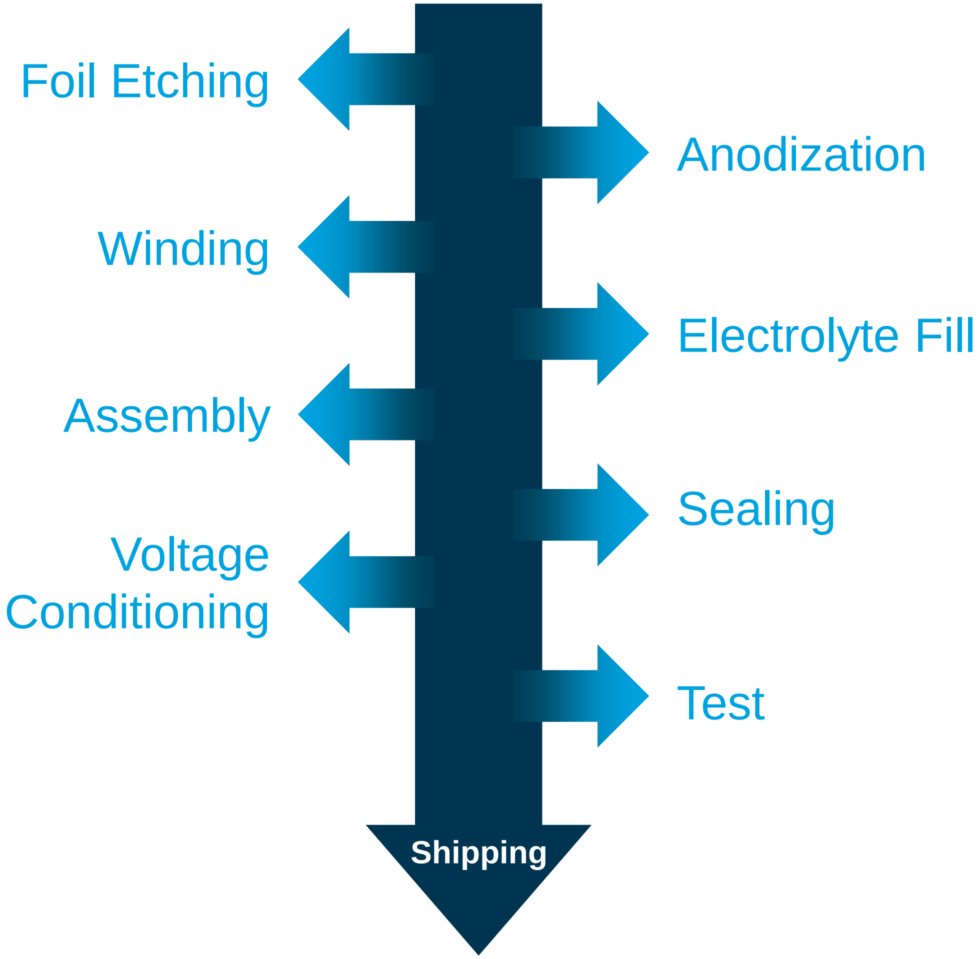


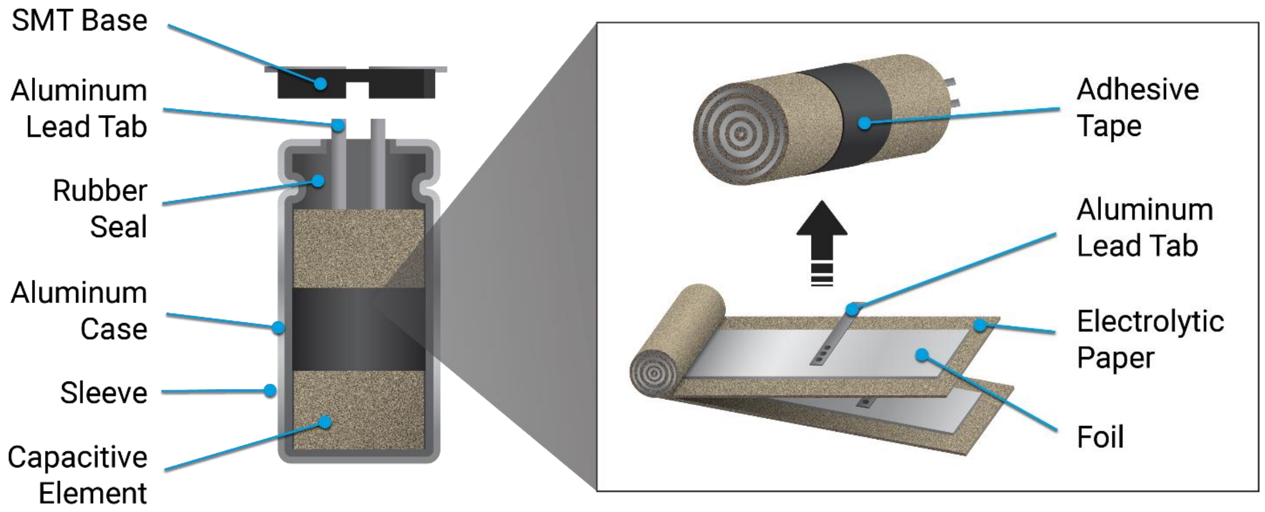


V chip SMT ALUMINUM ELECTROLYTIC

Construction & Type

SMT Aluminum Electrolytic Capacitors – Electrolyte Controls Device Characteristics

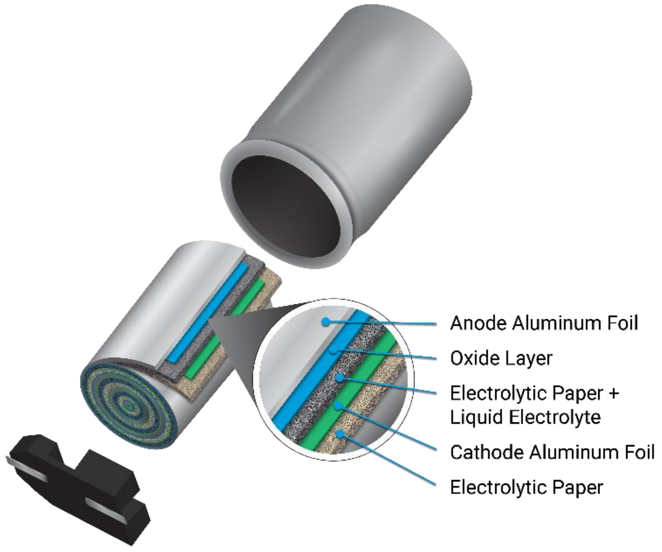




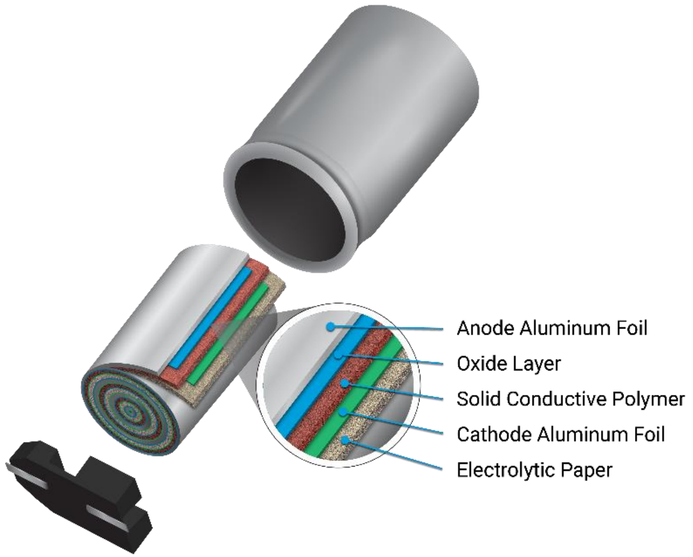
SMT ALUMINUM ELECTROLYTIC
Construction & Type

SMT Aluminum Electrolytic Capacitors – Electrolyte Controls Device Characteristics

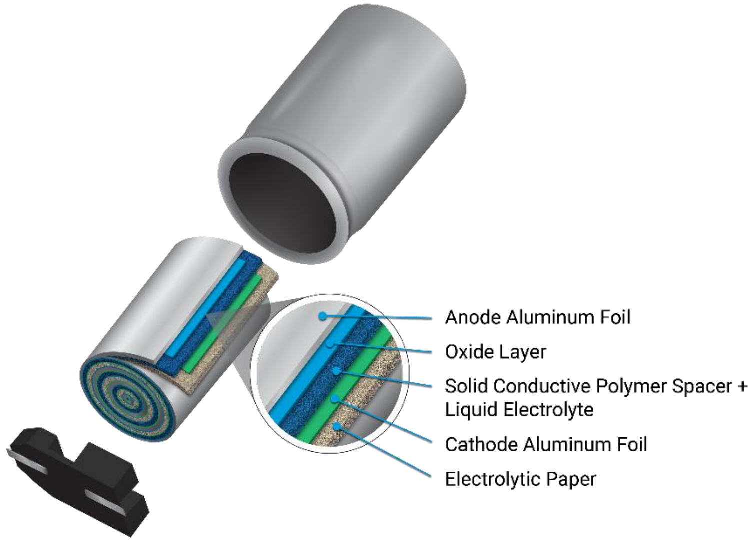
Wet Electrolytic



Polymer Electrolytic



Hybrid Electrolytic



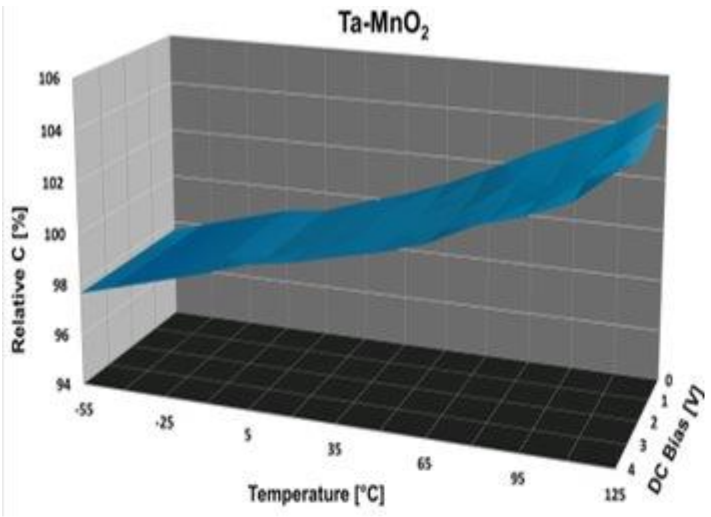
Applications by Electrolyte

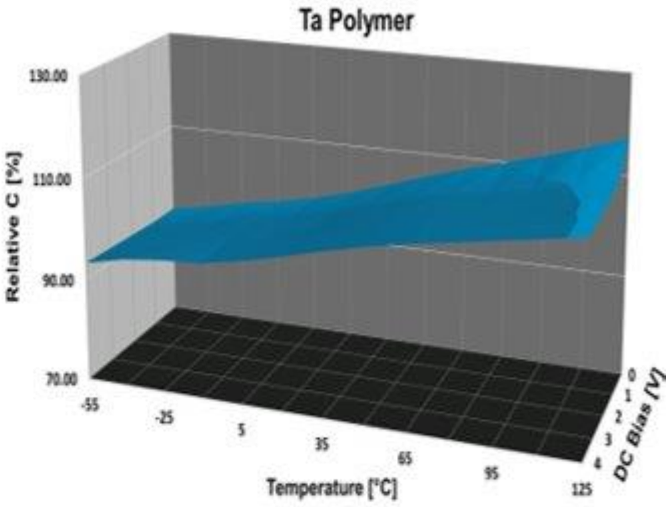
APPLICATION	WET	POLYMER	HYBRID
Power Conversion	++	+++	+++
Filtering	+++	+++	+++
Battery	+++	+	+++
Audio	+++	+++	+++
Base Station	+	++	+++
Industrial	+	+++	+++
Low Temperature	+	+++	++
High Temperature	++	+	+++
Extended Reliability		++	+++
High Vibration	+++	+	+++

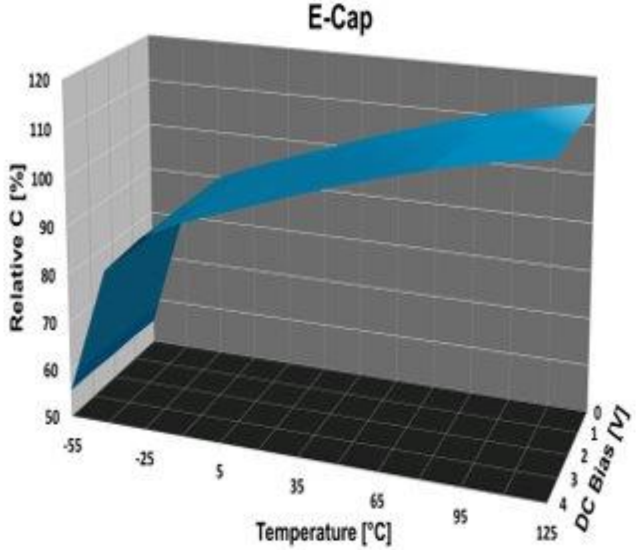
SPECIFICATION COMPARISON – 1210 EQUIVALENT EXAMPLE

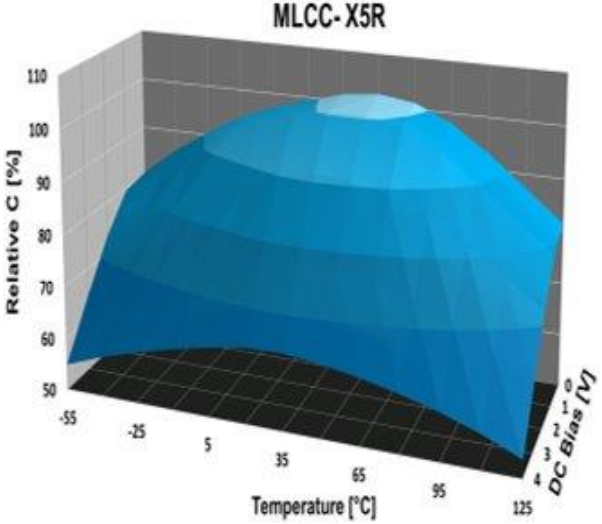
ATTRIBUTES	MLCC		STANDARD TA CHIP		POLYMER TA CHIP	
	COMMERCIAL	AEC-Q200	COMMERCIAL	AEC-Q200	COMMERCIAL	AEC-Q200
Max Capacitance 1210	100uF	10uF	150uF	100uF	220uF	47uF
Voltage Range 1210	4v - 50v	16v - 100v	4v - 50v	4v - 50v	4v - 50v	4v - 50v
Typical ESR 1210	7 - 15mOhms	10 - 40mOhms	300 - 800mOhms	300 - 800mOhms	30 - 200mOhms	70 - 250mOhms
Temperature Range	-55°C - +85°C	-55°C - +125 / +150°C	-55°C - +125°C	-55°C - +125 / +200°C	-55°C - +105 / +125°C	-55°C - +125°C
Base Reliability	1% / 1000hrs	1% / 1000hrs	1% / 1000hrs	(0.05 - 1%) / 1000hrs	1% / 1000hrs	1% / 1000hrs
Primary Failure Mode	Short	Short	Short	Short	Short	Short
Lifetime (10% Cap loss @ Tmax / Vmax)	Indefinite	Indefinite	Indefinite	Indefinite	10,000hrs	10,000hrs
Recommended Voltage Derating	20%	20%	50%	50%	20%	20%
DISADVANTAGES	COMMERCIAL	AEC-Q200	COMMERCIAL	AEC-Q200	COMMERCIAL	AEC-Q200
Voltage Coefficient	Cap Loss vs V	Cap Loss vs V				
Piezo Noise	@ Audio Frequencies	@ Audio Frequencies				
Reverse Voltage			Not Allowed	Not Allowed	Not Allowed	Not Allowed

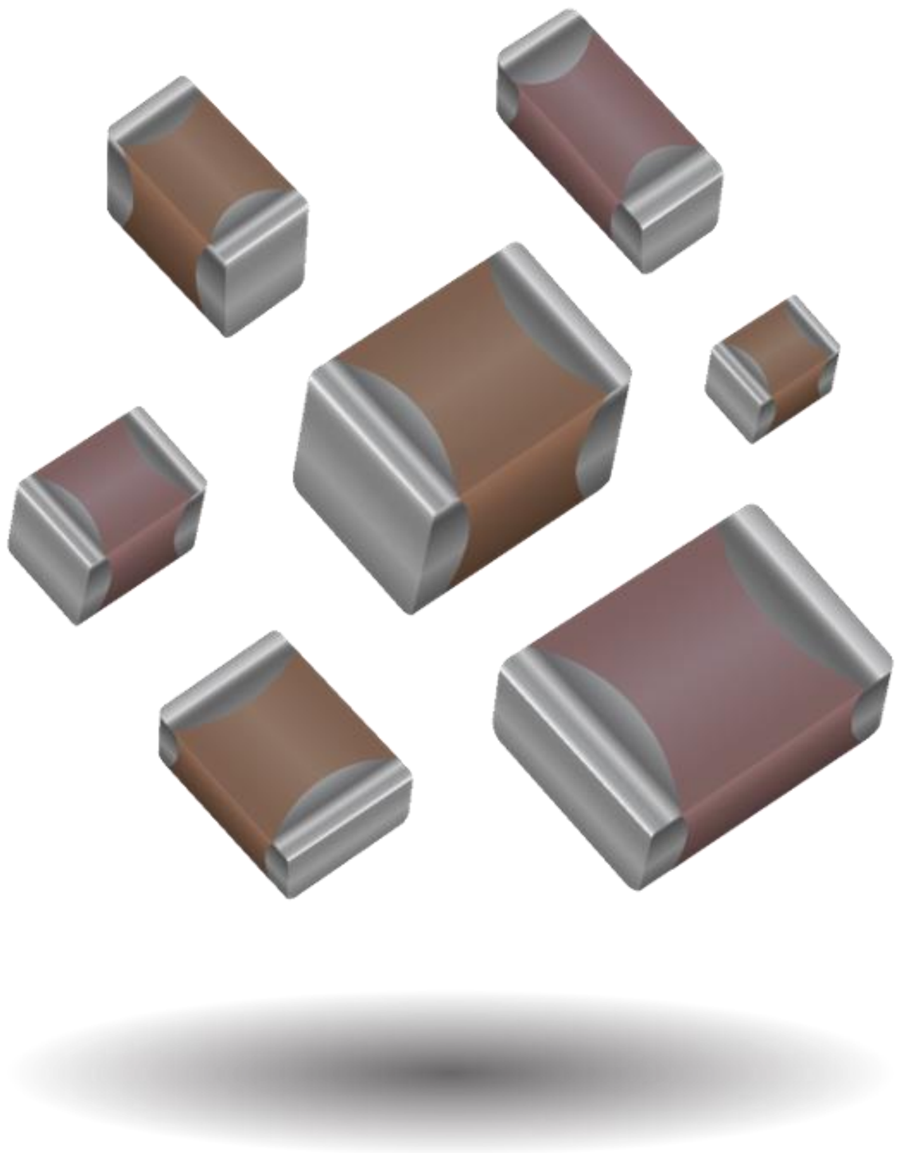
Electrolytic vs MLCC X5R Stability











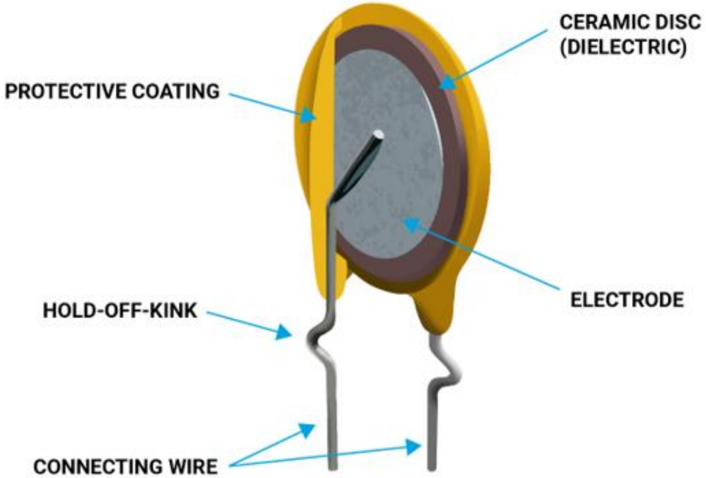
Multi-Layer Ceramic Capacitors

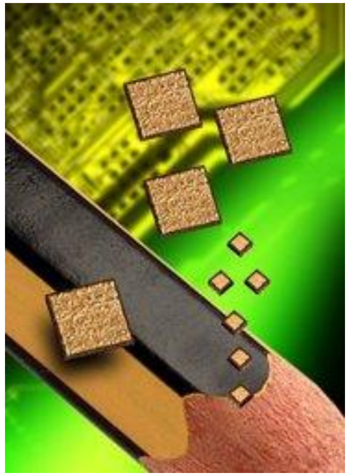
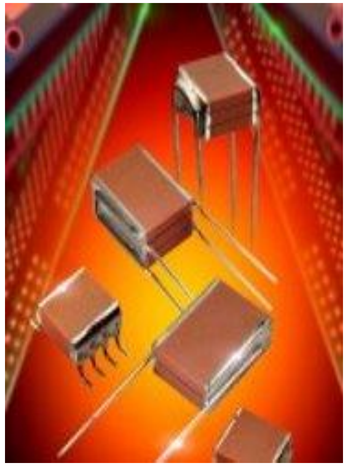
(MLCC)

Ceramic Capacitor Types

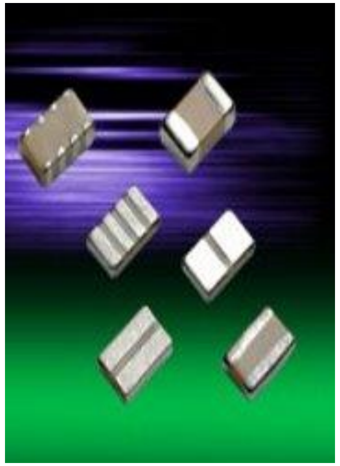
MLCCs are the most common capacitor type used





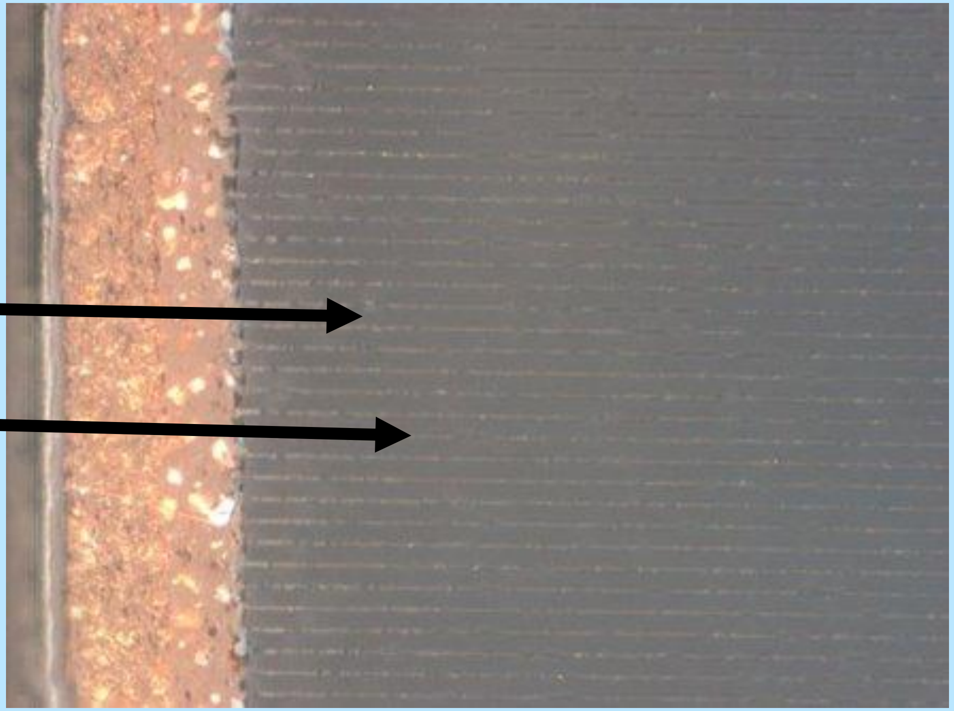




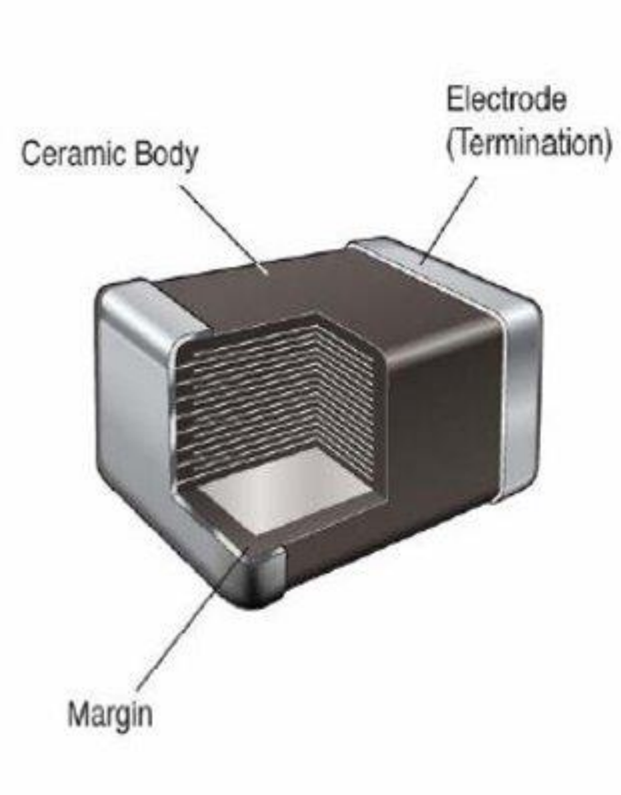

Ceramic Capacitors

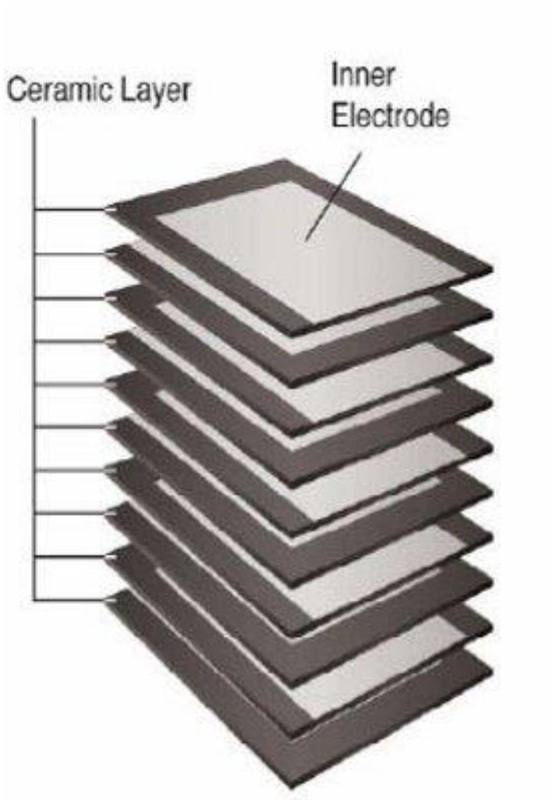
Electrostatic Capacitors

- **Fixed Value**
- **Ceramic is the dielectric**
- **Metal is the electrode**
- **Single or multiple layer**
- **Various shapes/forms**
- **MOST COMMON is the MLCC – Multi-Layer Ceramic Capacitor**

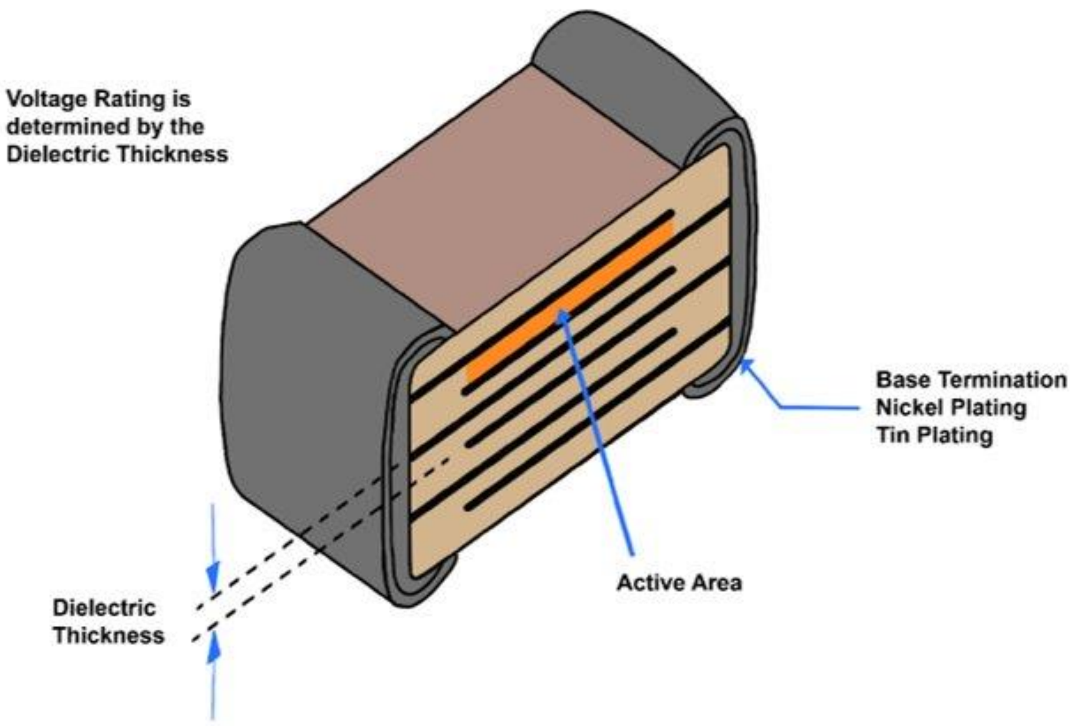


MLCC Design Considerations

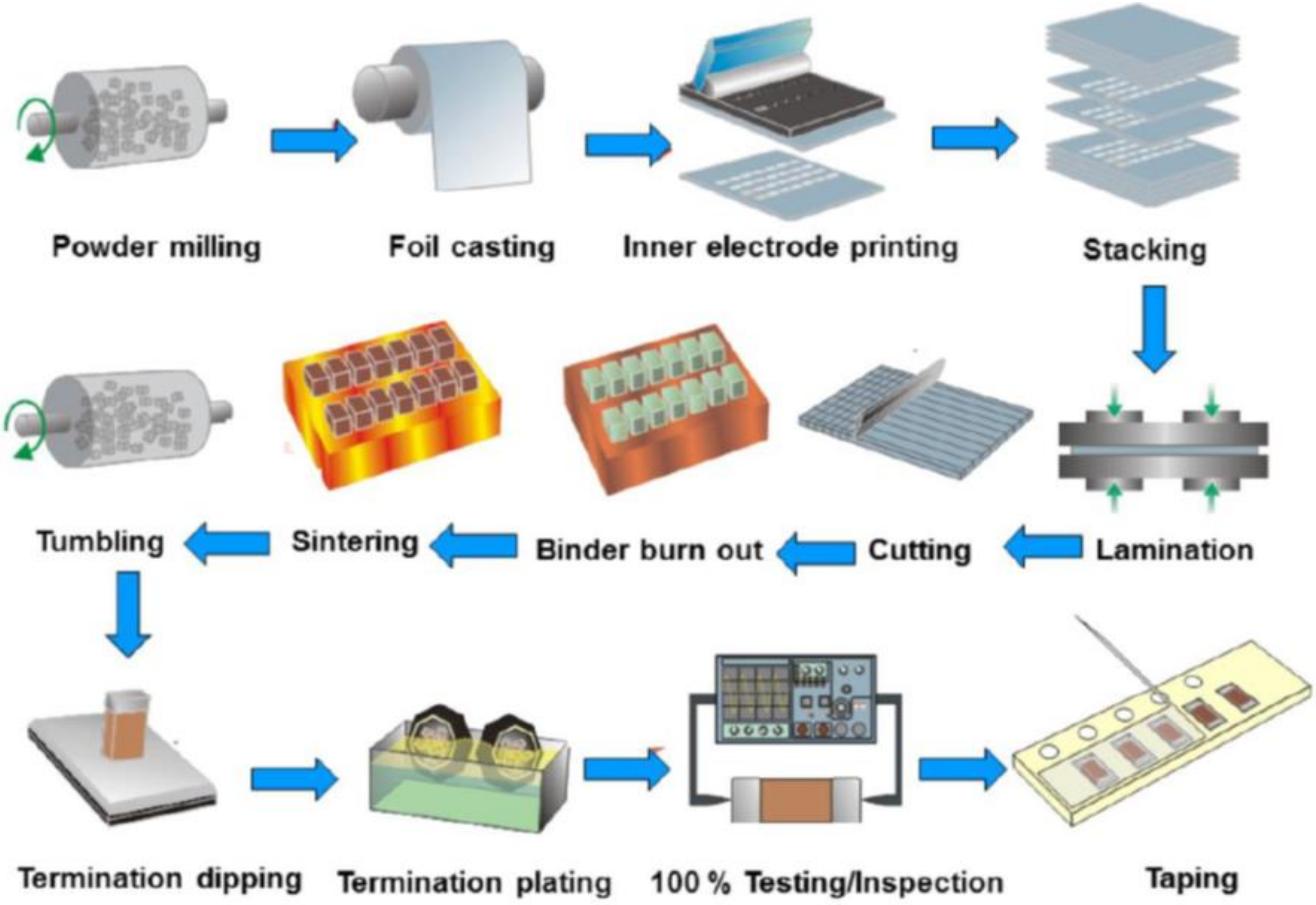




$$\text{Capacitance} = \frac{\#\ \text{Layers} \times \text{Dielectric Constant} \times \text{Active Area}}{\text{Dielectric Thickness}}$$



MLCC Dry Process



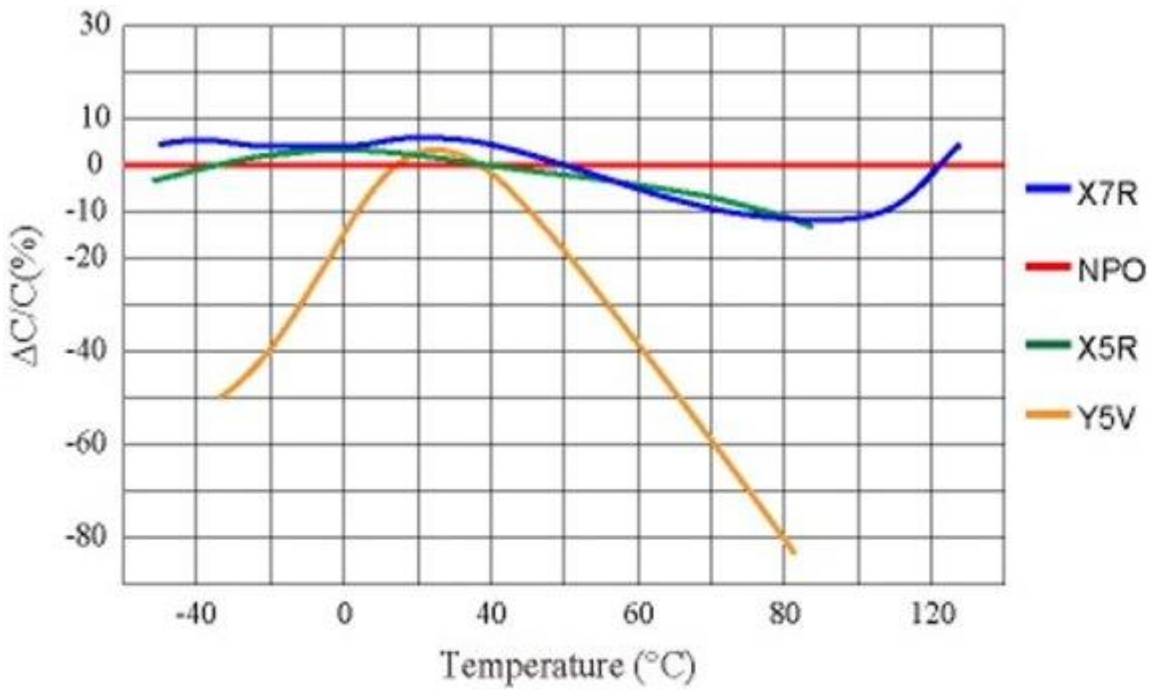
MLCC Performance

Mostly controlled by the dielectric

COMMON DIELECTRIC TYPES USED:

TYPE	CLASS	TEMPERATURE RANGE	VARIATION DUE TO TEMPERATURE
C0G	Class I	-55°C to +125°C	+/-15ppm/°C
U2J	Class I	-55°C to +125°C	-750ppm/°C
X8R	Class II	-55°C to +150°C	±15%
X8L	Class II	-55°C to +150°C	±15%, then -40% from 125°C to 150°C
X7R	Class II	-55°C to +125°C	±15%
X7S	Class II	-55°C to +125°C	±22%
X6S	Class II	-55°C to +105°C	±22%
X5R	Class II	-55°C to +85°C	±15%
Y5V	Class III	-30°C to +85°C	+22% / -82%
Z5U	Class III	+10°C to +85°C	+22% / −56%

EXAMPLE OF CAP VS TEMPERATURE:



MLCC Performance

Mostly controlled by the dielectric

Dielectric Stability Code Explanation

First Character

LETTER	LOW TEMP
X	-55C (-67F)
Y	-30C (-22F)
Z	+10C (+50F)

Second Character

DIGIT	HIGH TEMP
2	+45C (+113F)
4	+65C (+149F)
5	+85C (+185F)
6	+105C (+221F)
7	+125C (+257F)

Third Character

LETTER	CHANGE
D	+/-3.3%
E	+/-4.7%
F	+/-7.5%
P	+/-10%
R	+/-15%
S	+/-22%
T	+22% / -33%
U	+22% / -56%
V	+22% / -82%

Definitions of Application Classes for Ceramic Capacitors

IEC/EN 60384-1
IEC/EN 60384-8/9/21/22

Class 1 Ceramic capacitors offer high stability and low losses for resonant circuit applications.

Class 2 Ceramic capacitors offer high volumetric efficiency for smoothing, by-pass, coupling, and decoupling applications.

Class 3 Ceramic capacitors are barrier layer capacitors which are not standardized anymore.

EIA RS-198

Class I (or written class 1) Ceramic capacitors offer high stability and low losses for resonant circuit applications.

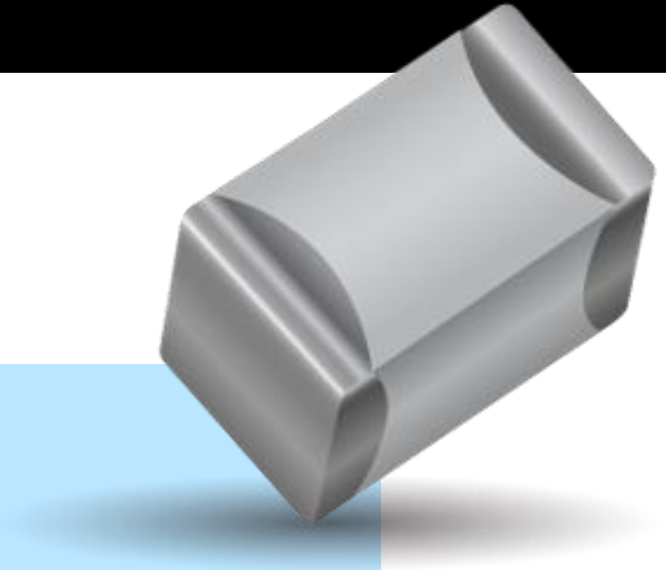
Class II (or written class 2) Ceramic capacitors offer high volumetric efficiency with change of capacitance lower than -15% to +15% and a temperature range greater than -55°C to +125°C, for smoothing by-pass, coupling, and decoupling applications.

Class III (or written class 3) Ceramic capacitors offer higher volumetric efficiency than EIA class 2 and typically change by -22% to +56% over a lower temperature range of 10°C to 55°C. They can be substituted with EIA class 2-Y5U/Y5V or Z5U/Z5V capacitors.

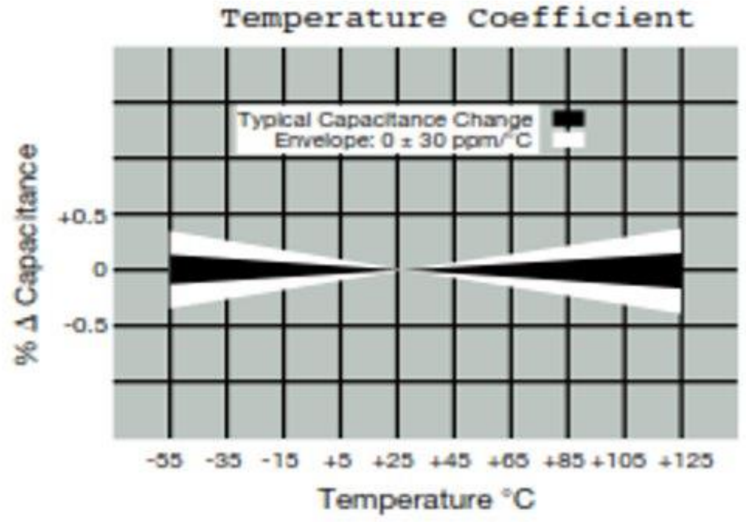
Class IV (or written class 4) Ceramic capacitors are barrier layer capacitors which are not standardized anymore.

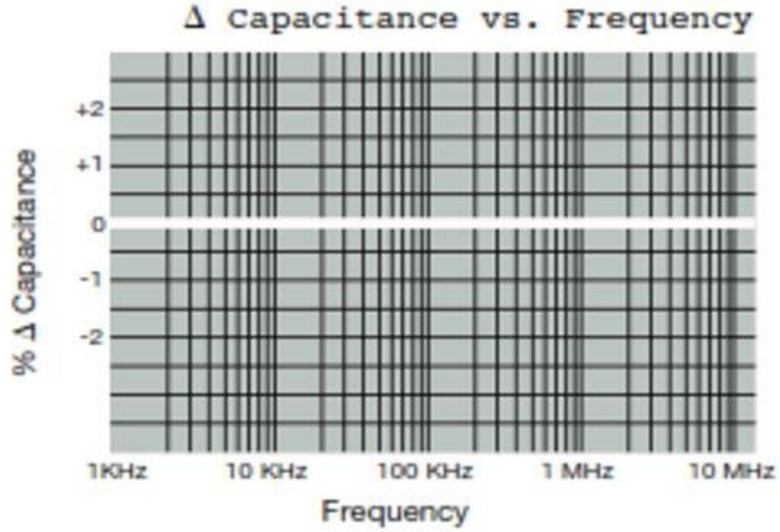
Class 1 Type

Ceramic Capacitors



- Very accurate values.
- Formulations exist that can provide temperature-compensation.
- Near Zero capacitance variation with applied voltage, Temperature variation & time.
- Exhibit lowest losses – ideal in resonant circuit applications or precisely defined applications – timing, sample & hold, tuning.





Class 2 Type

Ceramic Capacitors

- These have a dielectric with a high permittivity and therefore a **better volumetric efficiency** than class 1 capacitors, but **lower accuracy and stability.**
- The ceramic dielectric is characterized by a **nonlinear change of capacitance over the temperature range**, varies with applied voltage and has an aging effect (reduces with time).
- The **most widely used** classification used in designs.
- Class 2 capacitors are made of ferrolectric materials such as barium titanate (BaTiO) and suitable additives
- They are **suitable for bypass, coupling and decoupling applications** or for frequency discriminating circuits where low losses and high stability of capacitance are less important. Also applications that require the capacitor to maintain only a minimum value of capacitance, for example, buffering and filtering in power supplies and coupling and decoupling of electric signals.

Class 2 Type

Ceramic Capacitors

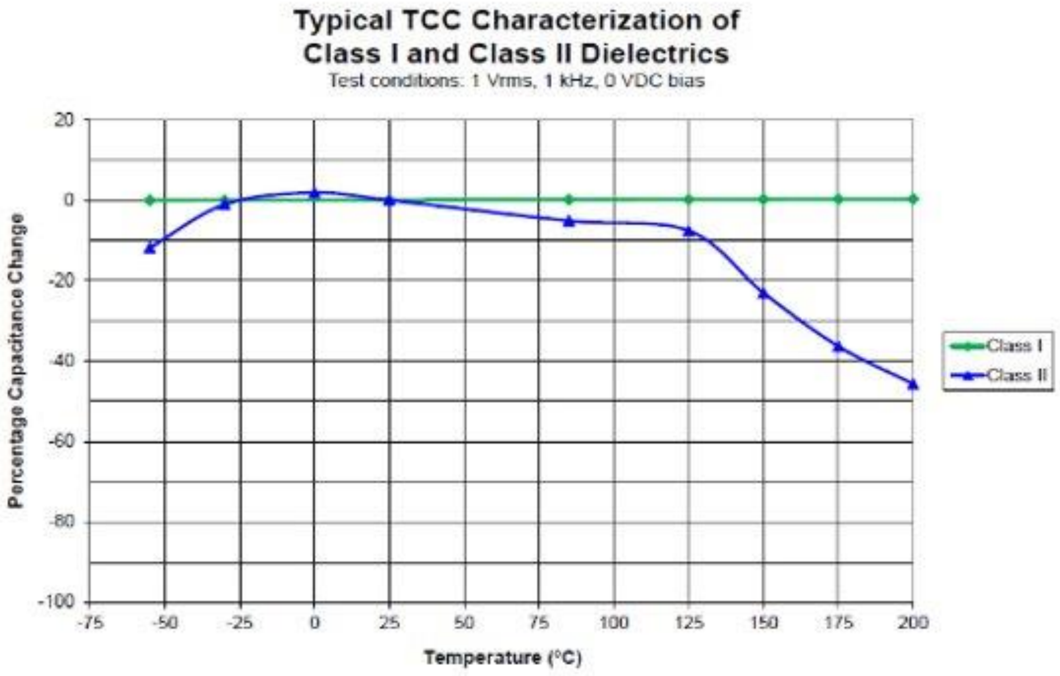
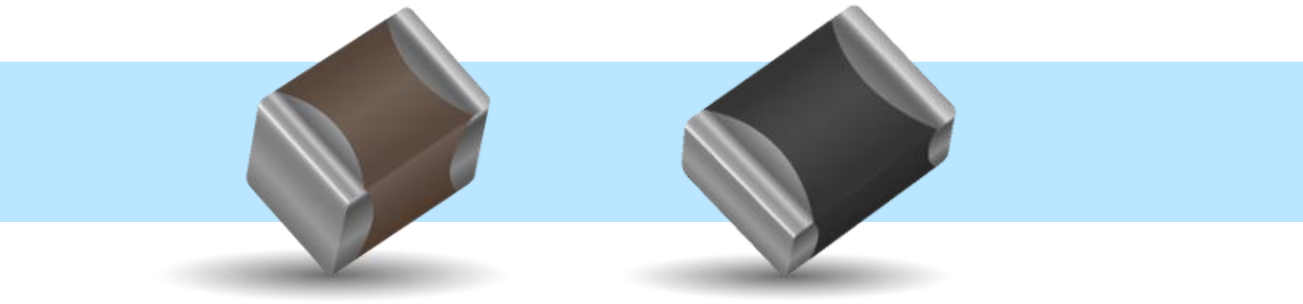


Figure 2: Typical TCC Characterization of Class I and Class II Dielectrics (1VRms, 1 kHz, 0 VDC bias)



Code system regarding to EIA RS-198 for some temperature ranges and inherent change of capacitance

Letter code low temperature	Number code upper temperature	Letter code change of capacitance over the temperature range
X = −55 °C (−67 °F)	4 = +65 °C (+149 °F)	P = ±10%
Y = −30 °C (−22 °F)	5 = +85 °C (+185 °F)	R = ±15%
Z = +10 °C (+50 °F)	6 = +105 °C (+221 °F)	S = ±22%
	7 = +125 °C (+257 °F)	T = +22/−33%
	8 = +150 °C (+302 °F)	U = +22/−56%
	9 = +200 °C (+392 °F)	V = +22/−82%

Example:

X7R = -55 ºC , +125 ºC , +- 15%

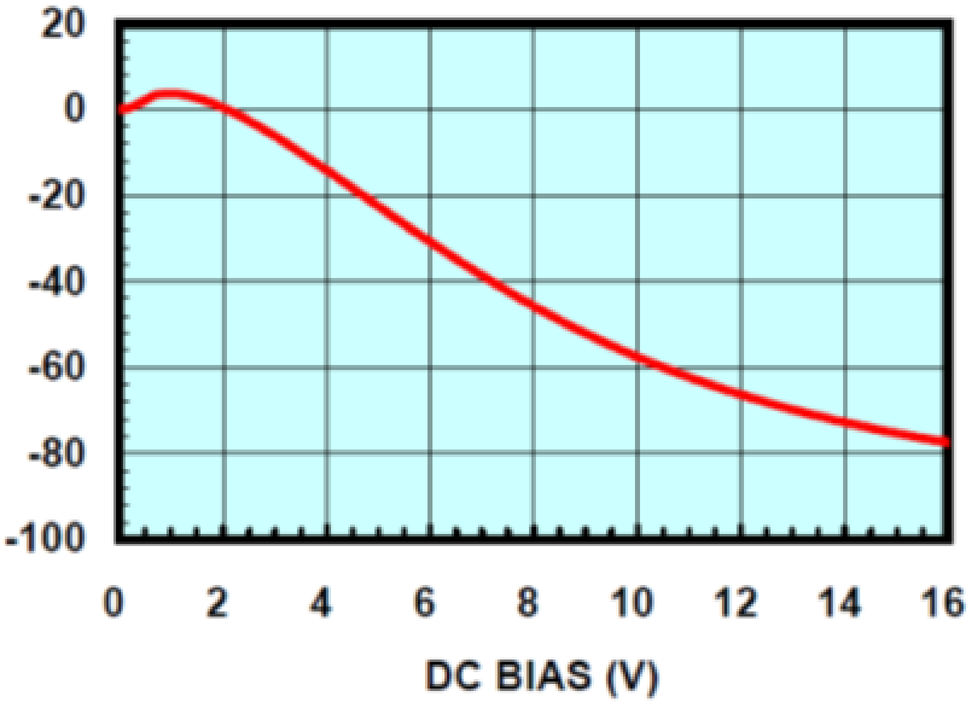
X8R = -55 ºC , +150 ºC , +-15%

MLCC Stability

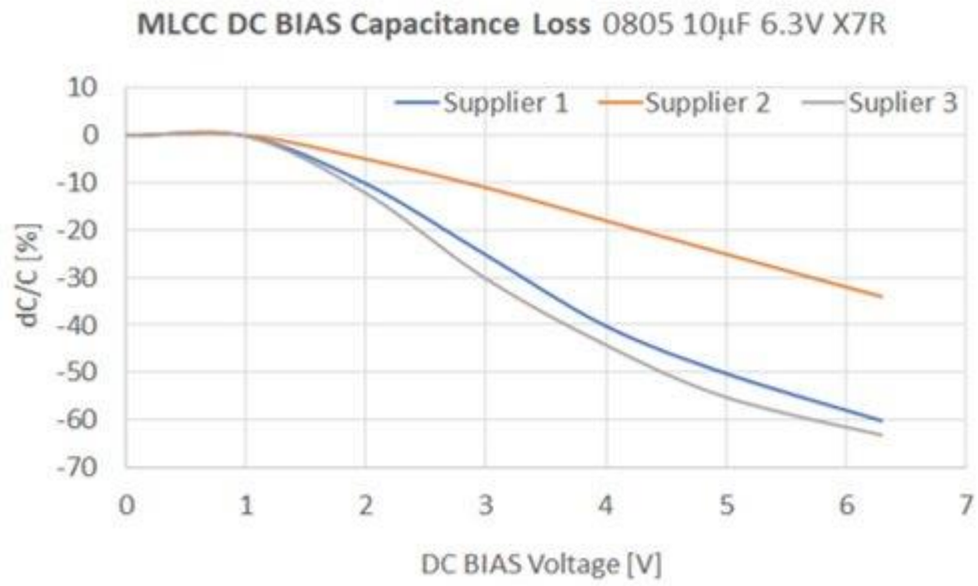
DC Bias Examples

In addition to capacitance changing in accordance to temperature – capacitance changes with applied DC voltage, AC voltage and time.

DC Bias varies by dielectric lot



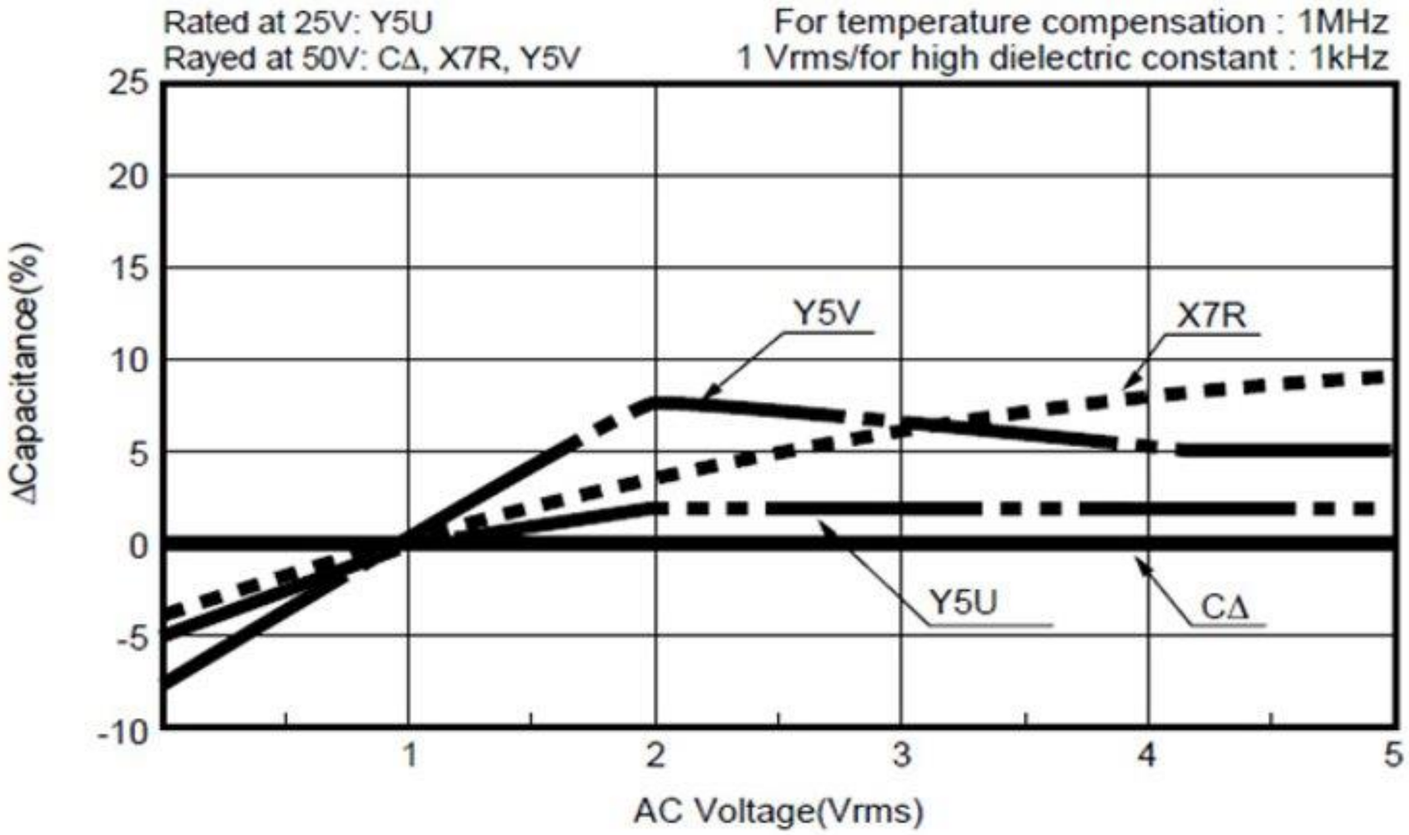
DC Bias varies by manufacturer



MLCC Stability

AC Bias Example

In addition to capacitance changing in accordance to temperature – capacitance changes with applied DC voltage, AC voltage and time.



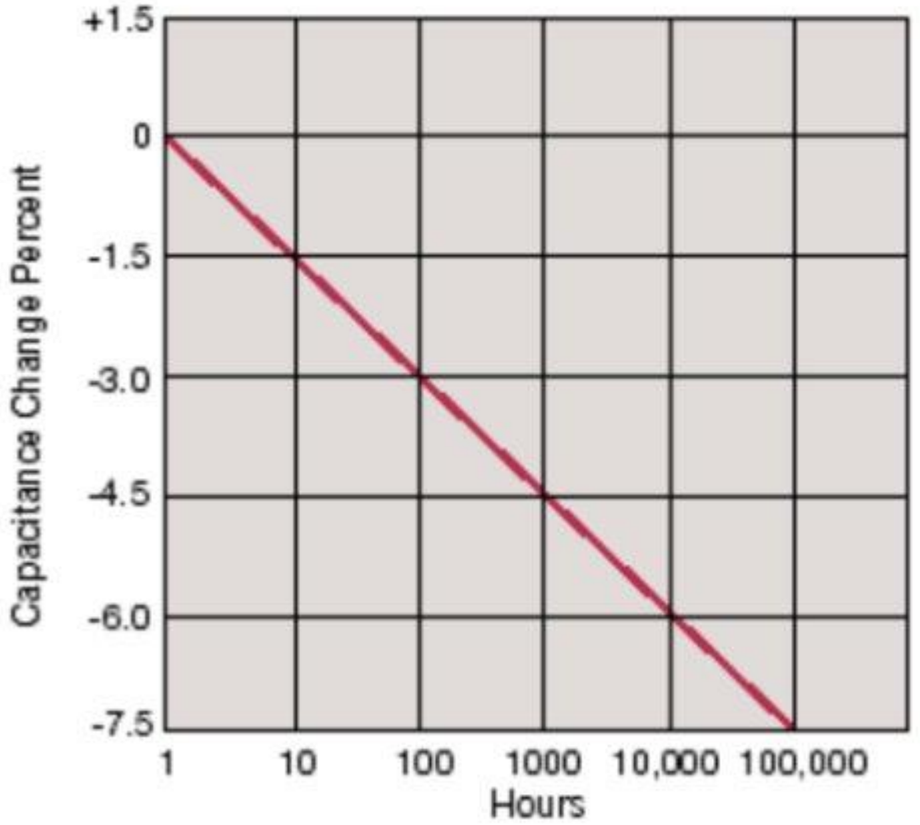
Source: EPCI

MLCC Stability

Aging Example

In addition to capacitance changing in accordance to temperature –capacitance changes with applied DC voltage, AC voltage and time.

Typical Curve of Aging Rate
X7R



Characteristic	Max. Aging Rate %/Decade
C0G (NP0)	None
X7R, X5R	2
Y5V	7

MLCC Stability Recap

If you select a **X5R 0805 10uF 6.3V** capacitor as 5V coupling capacitor in operating amplifier the capacitor may exhibit (depending to manufacturer):

- **60% drop of capacitance** due to DC voltage 5V close to 6.3V maximum rated voltage (as per typical data provided by manufacturer)
- **15% drop of capacitance** due to AC voltage being 10mV (as per typical data provided by manufacturer)
- **10% drop of capacitance** due to operating temperature (as per specification sheet)
- **5% drop of capacitance** each time decade (as per specification sheet)

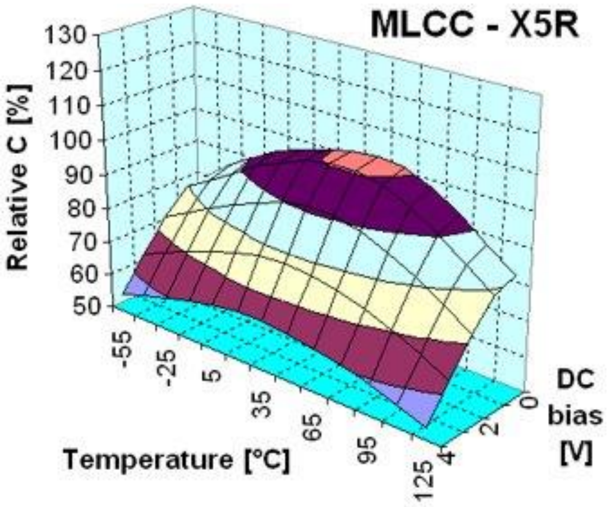
The total capacitance value at actual condition is then defined as multiplications of the capacitance drop factors.

$$C_{actual} = C_{rated} * F_{DCV\ drop} * F_{ACV\ drop} * F_{temp\ drop} * F_{ageing\ drop}$$

(In example above)

$$C_{actual} = 10uF * 0.4 * 0.85 * 0.9 * 0.95 = 2.9uF$$

The actual capacitance value of the 10uF 6.3V MLCC X5R capacitor at the operating condition above is expected to be 2.9 uF.



Excerpt from EPCI

MLCC Reliability Example

(General example – a snapshot in time)

				AT RATED VOLTAGE & TEMPERATURE		AT TYPICAL USAGE CONDITION (0.5 x RVDC & 50°C)			
DIELECTRIC GROUP	LOTS TESTED	PIECES TESTED	DEVICE HOURS	EQUIVALENT DEVICE HOURS	FAILURE RATE (1/)	EQUIVALENT D EVICE HOURS	FAILURE RATE (1/)	FAILURE R ATE FITS - (2/)	MTBF
NPO/COG	366	43390	2.81 x	2.25 x	0.010	1.80 x	1.28 x	0.013	7.80 x
X7R/X7S	3589	453849	2.37 x	1.90 x	0.068	1.52 x	8.50 x	0.085	1.18 x
X5R	12	1305	3.48 x	2.78 x	0.083	1.25 x	1.84 x	1.839	5.44 x

Notes: 1/ Failure Rates are calculated in Percent Per 1000 Hours at 90% Confidence Level
2/ 1 Fit+1Failure in 10^9 Hours (PPM Per 1000 Hours) at 90% Confidence Level

This report contains a summary of FIT rates and MTBF for MLCC Ceramic Capacitors by dielectric formula. Due to the number of device hours required to calculate failure rates, all part numbers are combined by dielectric.

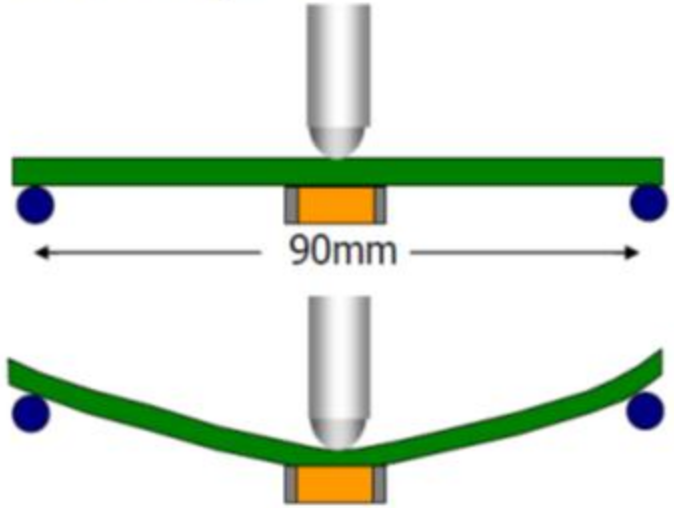
What can make a MLCC Fail? Stress

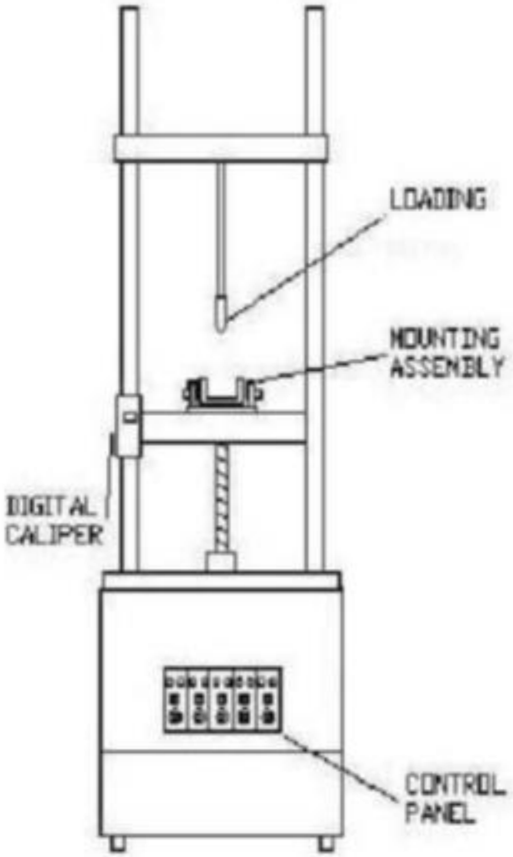
Board Bend Flex Test Procedure

Test Procedure as per AEC-Q200:

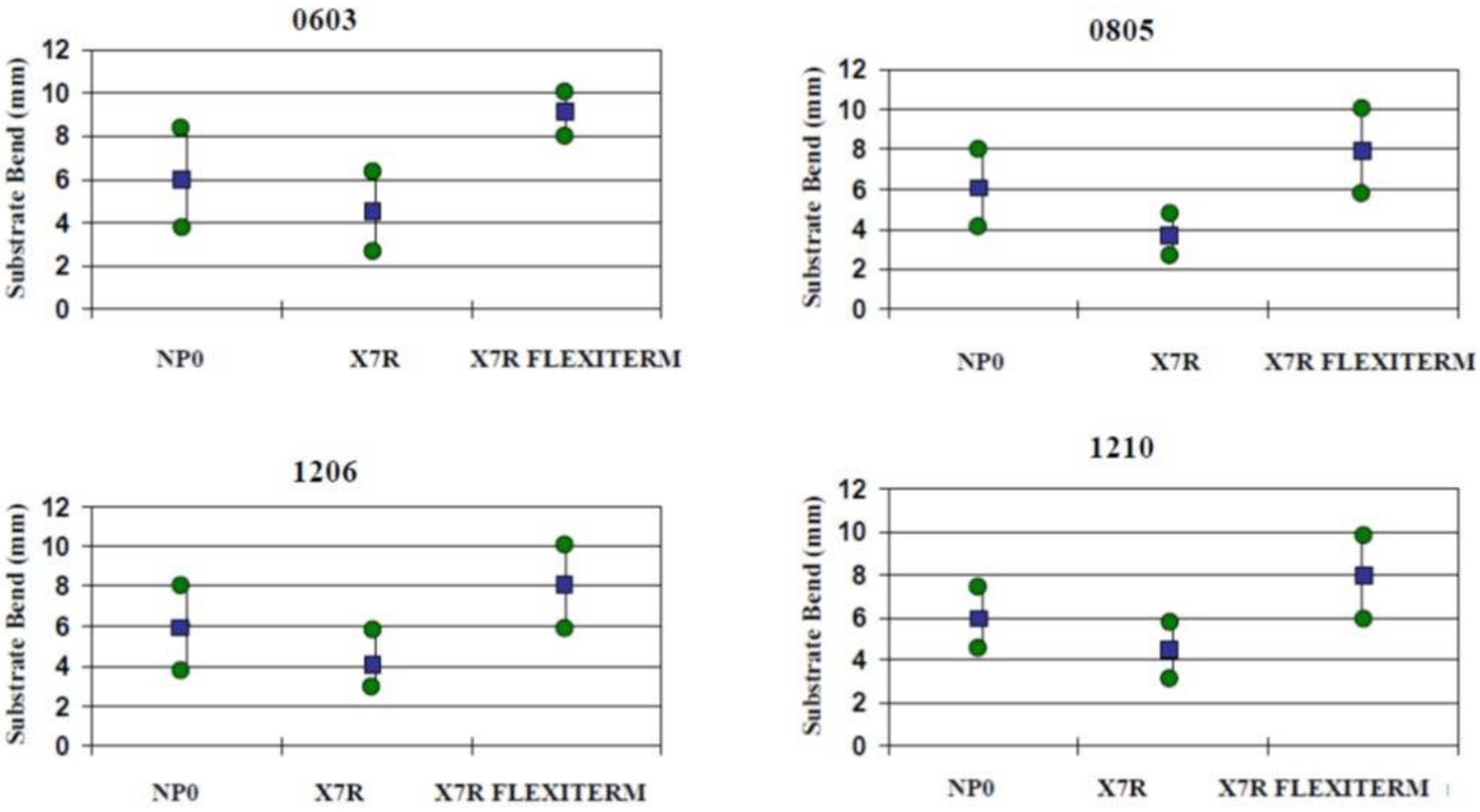
Minimum deflection spec: 2 mm (Class 2)

- Components soldered to FR4 PCB
- Board connected to the test equipment
- Motorized Moving Ram





MLCC Flexure Sensitivity

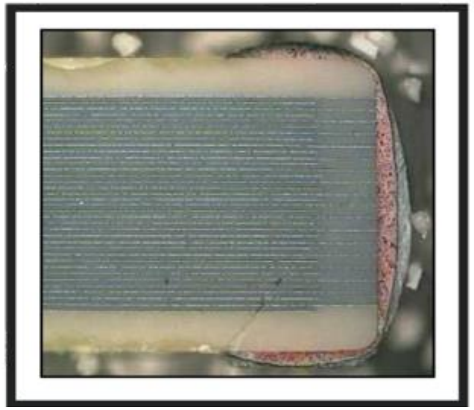


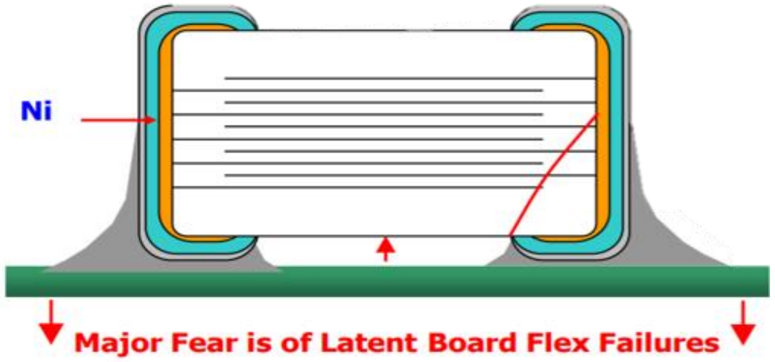
Board flex test is directly proportional to strain measurements on PCB

Mechanical Performance

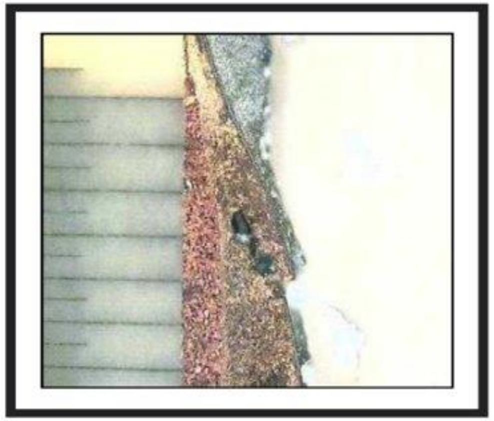
Cu Termination

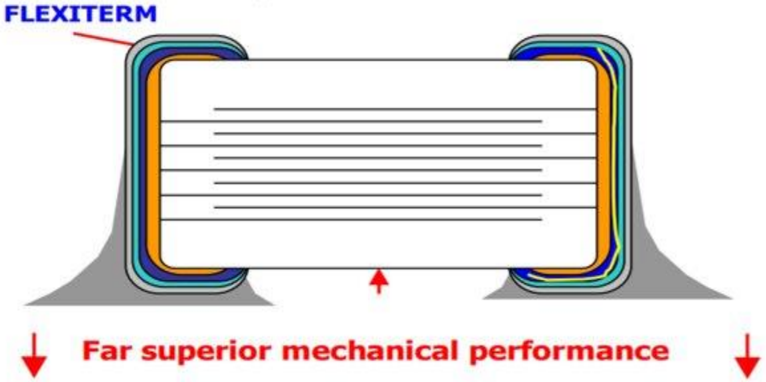
Standard MLCC termination





Flexible Termination





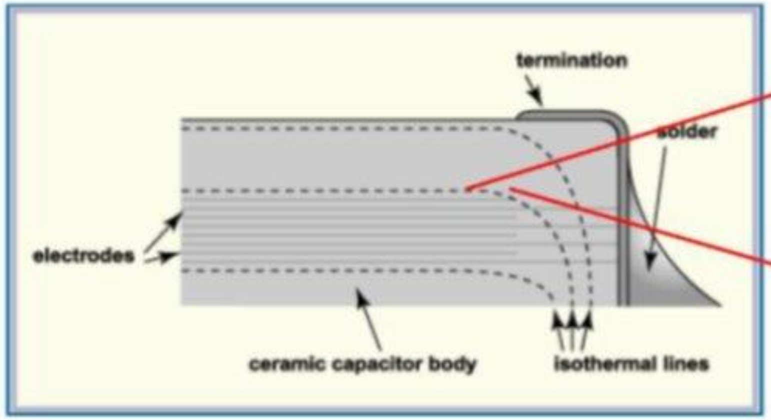
And if things go bad - What do DPAs tell us:

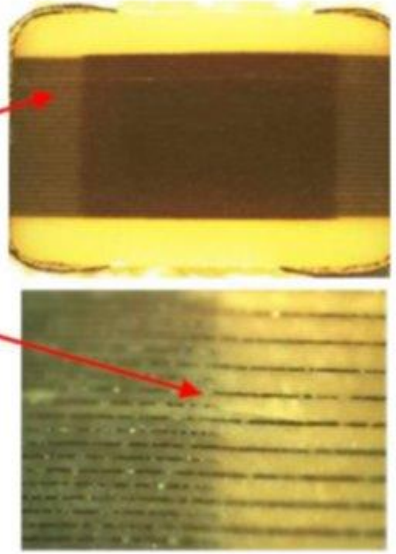
<u>Cause #1 - Thermal stress damage</u>

Cracks due to thermal stress occur due to rapid heating or cooling when soldering or if the body or terminations are touched directly with a soldering iron. The cracks typically originate at or near the end terminations and may propagate along isothermal lines therefore extending along and between internal electrodes.

This type of cracking can be caused by:

- An overly aggressive soldering profile (i.e., insufficient pre-heat, excessive peak temperature, too rapid ramp up or down).
- Re-working of the components using soldering irons. AVX recommends hot air reflow for re-working of capacitors. However, if soldering irons must be used, the tip must be kept <300°C and should not be allowed to make direct contact with the end terminations of the ceramic body.
- Extended exposure to high temperatures (peak soldering temp, burn-in hotspots)

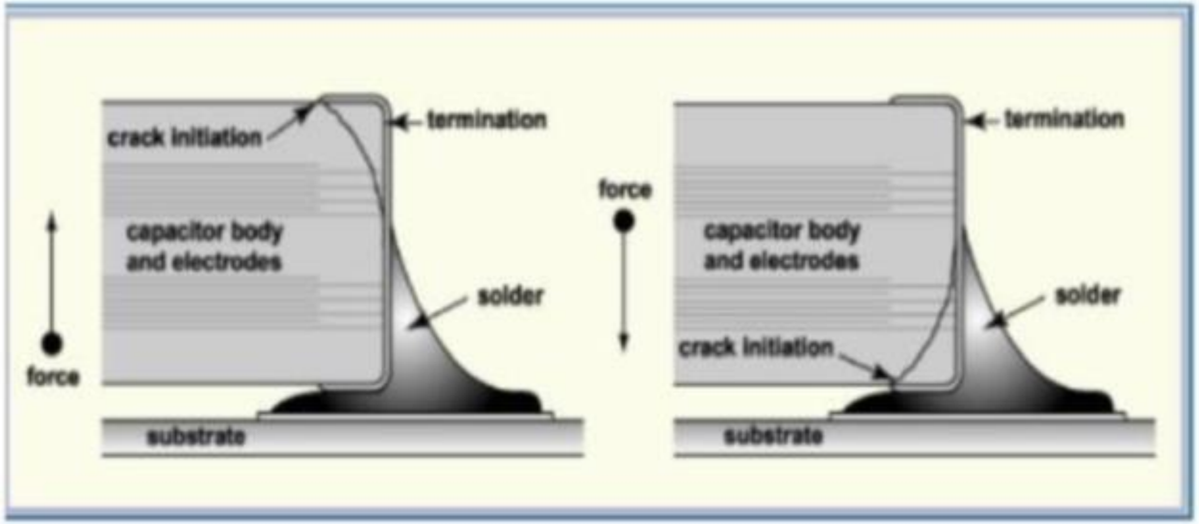




And if things go bad - What do DPAs tell us:

Potential Cause # 2 - failure due to mechanical stress.

One of the most common causes of failure is that the capacitor is stressed mechanically after being soldered to the circuit board as demonstrated below.



And if things go bad - What do DPAs tell us:

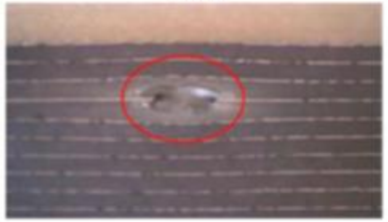
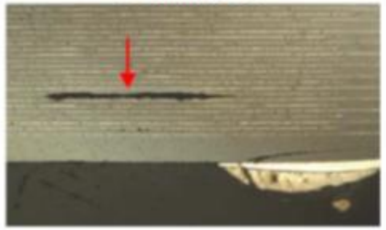
<u>*Cause # 3 - failure due to component fabrication defect*</u>

If a fabrication defect is present inside a ceramic capacitor this may result in a weakness in the diele
making it more susceptible to breakdown when under powered conditions.

Such defects generally fall into 3 general categories:

1. Voids
2. Thin dielectric layers
3. Delaminations

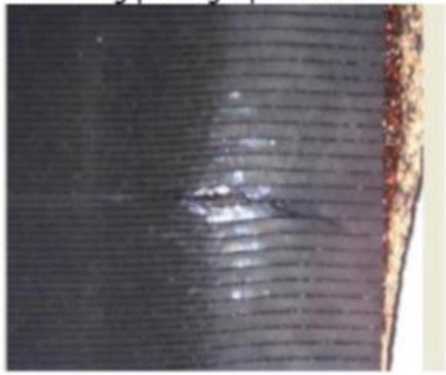
Examples are as follows:

Defect	Cause	Countermeasures
Void 	Particle entering the component during initial fabrication, then burning off during firing to leave a small void.	- Product is manufactured on class 10,000 clean room. - All lots are 100% tested for voltage and insulation resistance. - Samples from each lot are subjected to DPA (cross-sectioning) - Samples from each lot are subjected to reliability test at accelerated conditions.
Delamination 	Burn-out of organics or sintering process not optimized.	- Samples from each lot are subjected to DPA. - All lots are 100% tested for voltage and insulation resistance. - Samples from each lot are subjected to reliability test at accelerated conditions.
Thin Dielectric Layers 	Ceramic screening error during the deposition of the ceramic slip.	- Samples from each lot are subjected to DPA. - All lots are 100% tested for voltage and insulation resistance. - Samples from each lot are subjected to reliability test at accelerated conditions.

And if things go bad - What do DPAs tell us:

Cause # 4 - Electrical Overstress

If a component is subjected to a voltage higher than its dielectric can withstand then the dielectric may break down. Typically this results in a "point" type defect with cracking in the vicinity of the breakdown.
The following photograph demonstrates a dielectric layer broken down by applying excessive DC voltage.



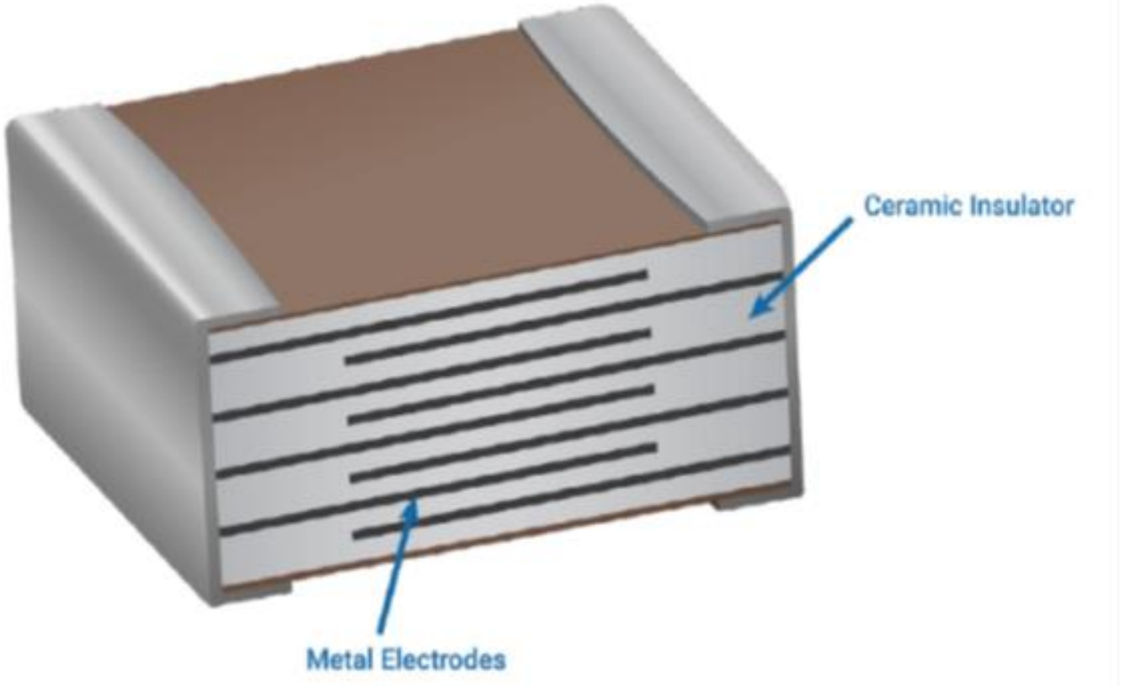
When the dielectric has been broken down in this fashion, current begins to flow between opposing electrodes, and eventually the component will start to heat until it melts the internal electrodes, ceramic and end terminations. Below is a photograph of one such component purposely shorted by applying excessive voltage and the having had 5 amps applied for a few minutes.

What about MLCC downsizing trend?

In the mid 1990's – typical minimum dielectric thickness was 5um and the MLCC had many hundred layers

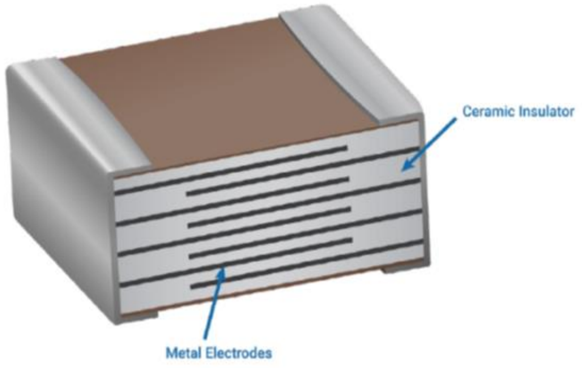
Today minimum dielectric thicknesses can be ~ 0,5um and > 1000 dielectric layers

E field stress on the dielectric has increased dramatically



What about MLCC downsizing trend?

The dielectrics used to attain high capacitance have Ferroelectric properties. The permittivity of those dielectrics decrease with increased electric field (from thinner dielectrics). Recall:



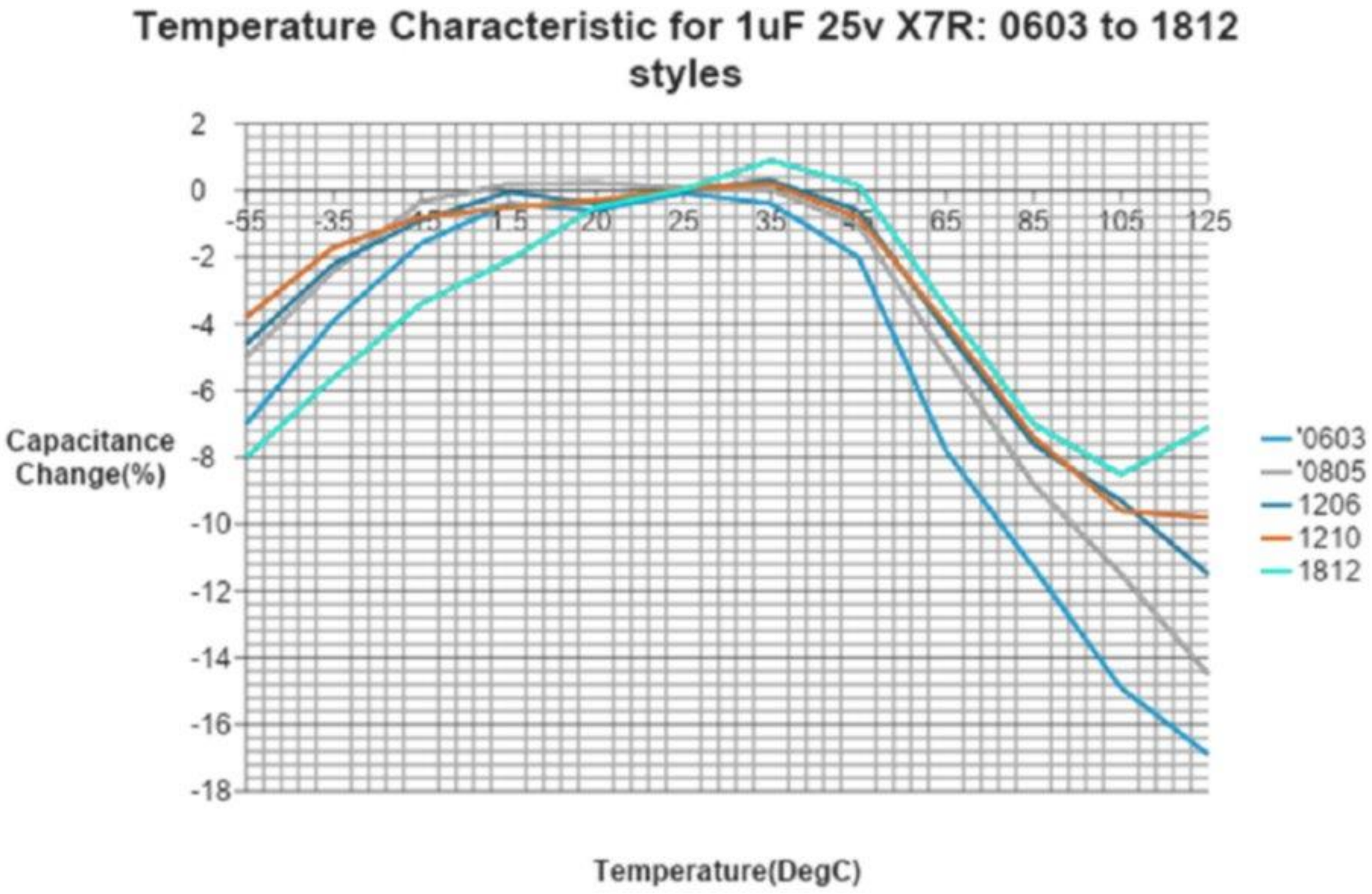
$$C = \varepsilon \frac{NA}{d}$$

This causes temperature and DC bias instability.
Something end users must understand and factor into designs.

See next slides:

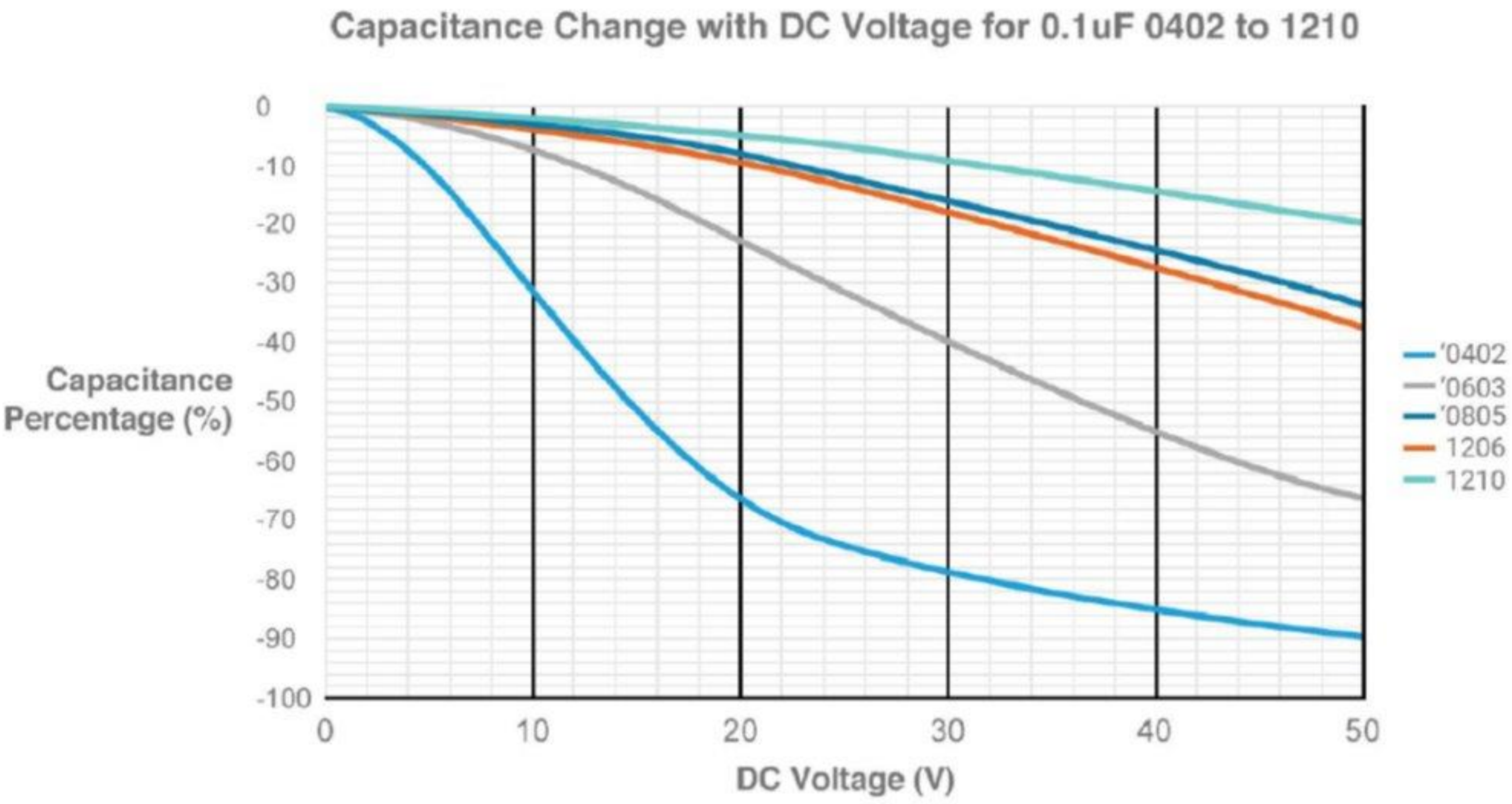
What about MLCC downsizing trend?

High E field effect on temperature stability



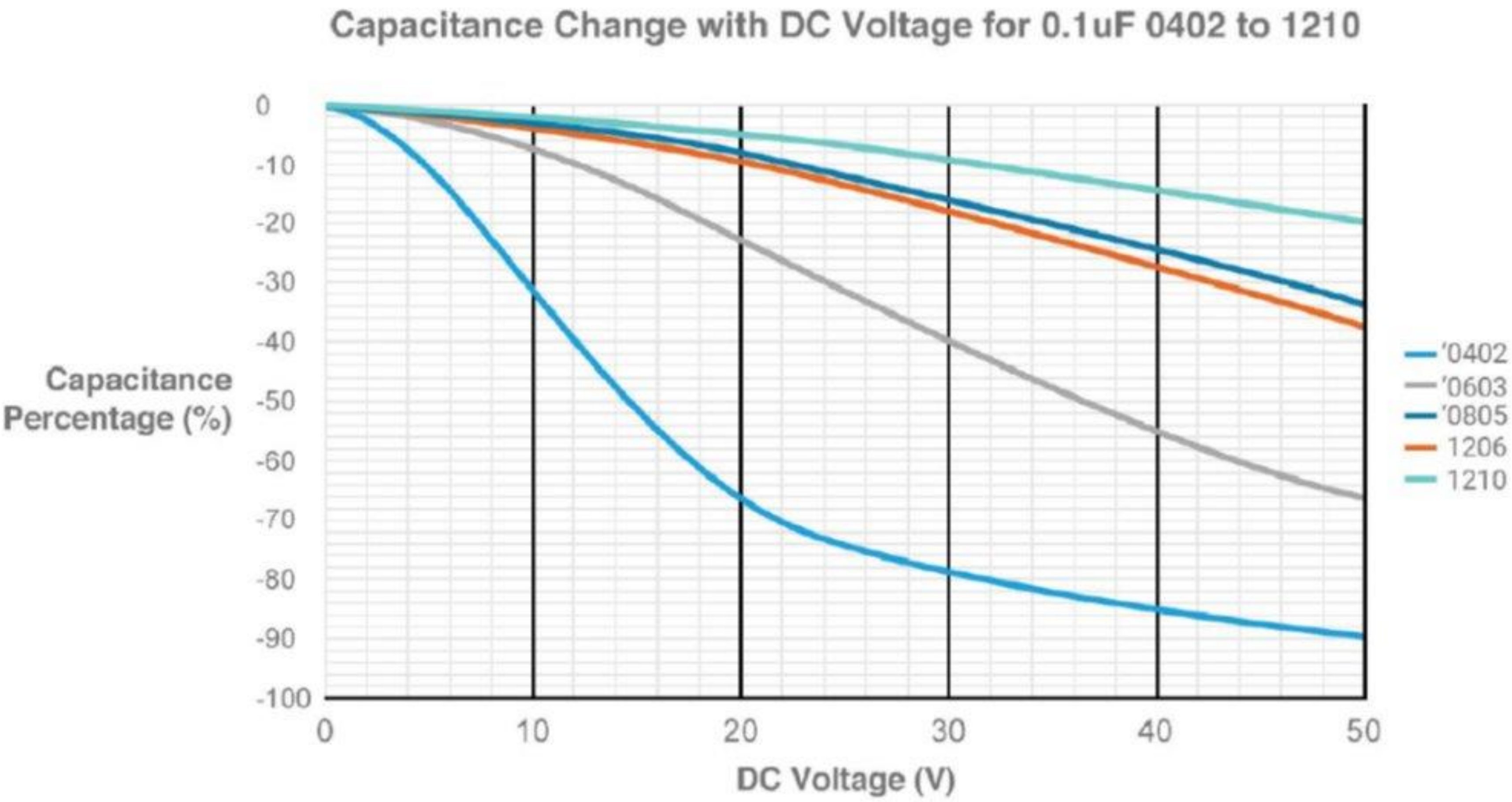
What about MLCC downsizing trend?

High E field effect on DC Bias stability

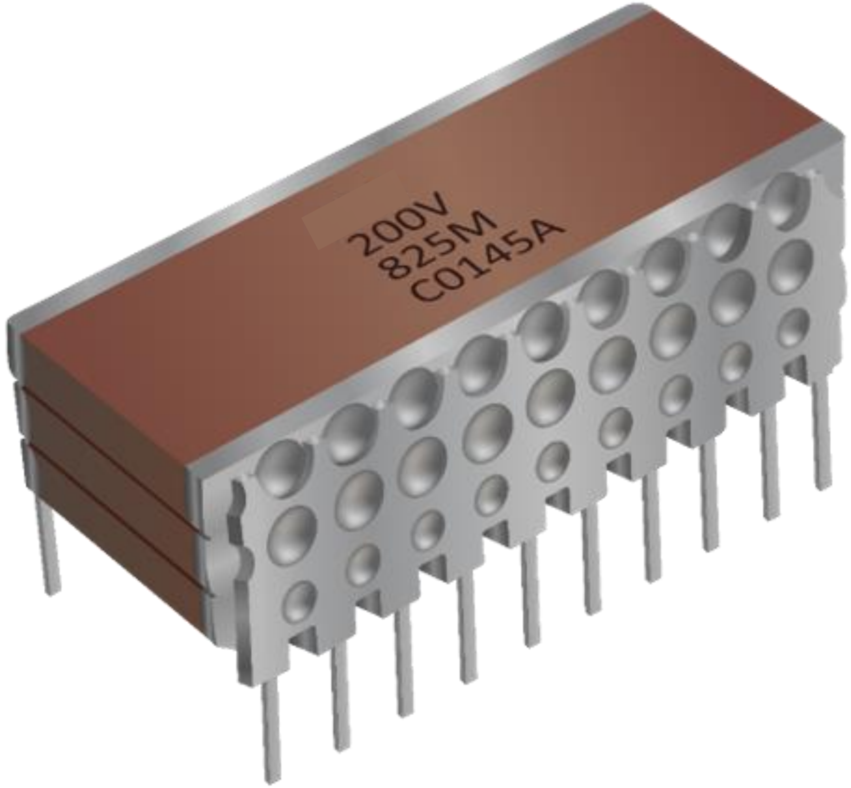


What about MLCC downsizing trend?

Dielectric thickness affects reliability



What about Large MLCC Trends?

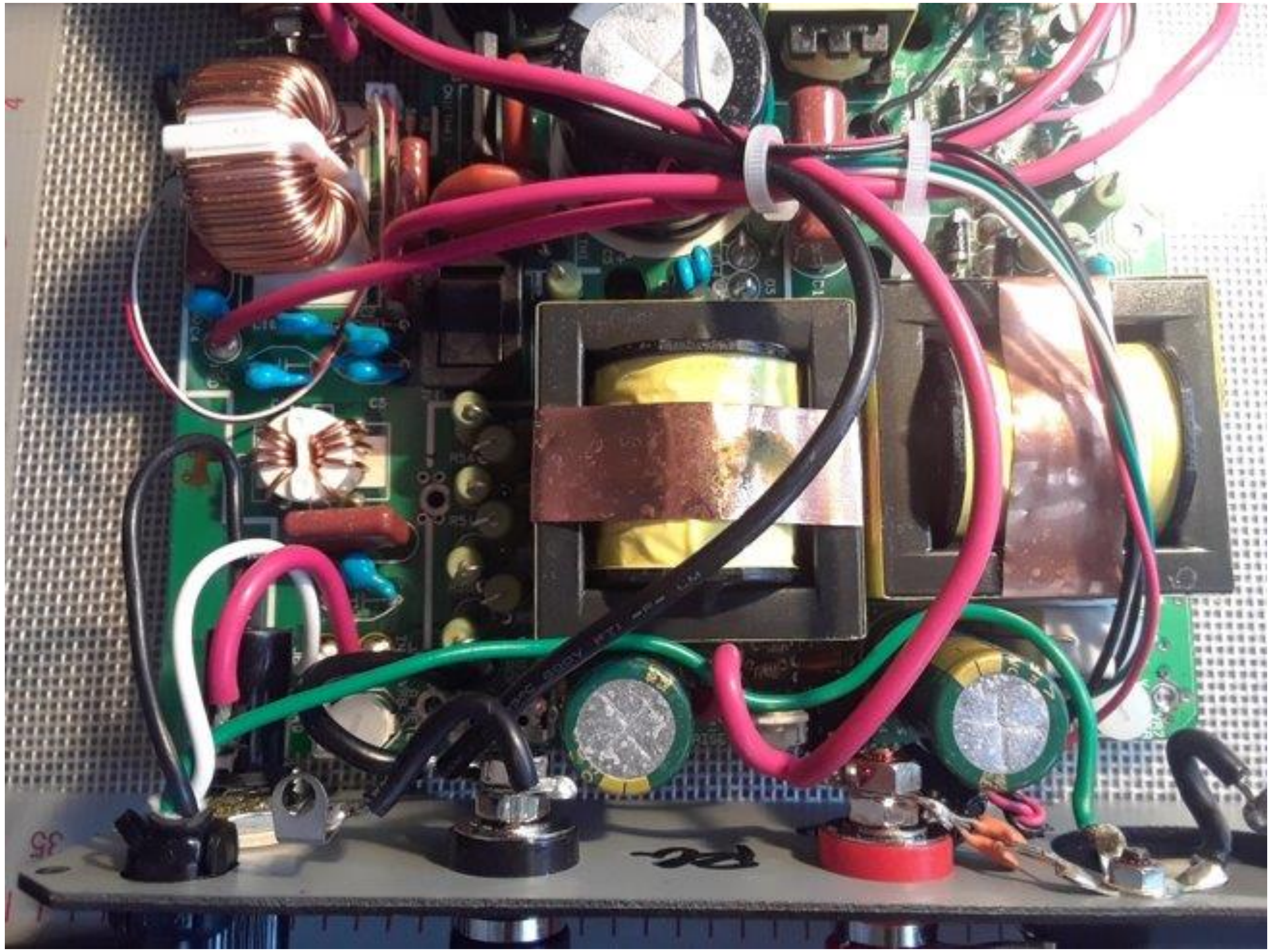


MLCC Stacked Capacitors

High Reliability –
‘Reduced’ Inductance
‘Reduced’ ESR

Why Stacked Ceramics?

Efficiency Through ESR & ESL Reduction



Stacked caps offer improvements in capacitor:

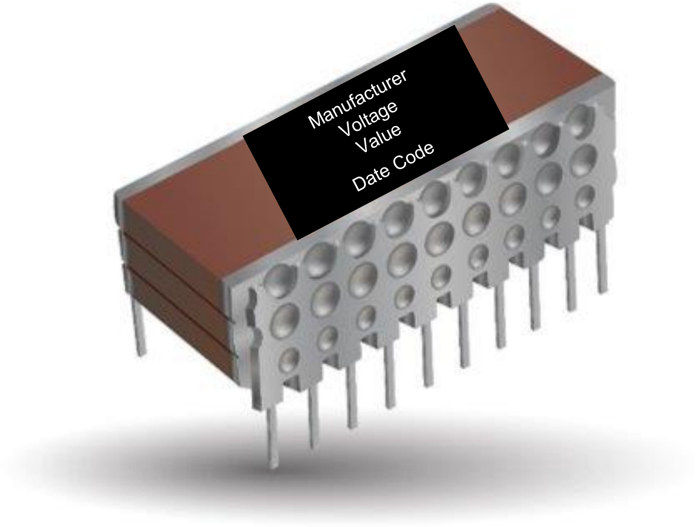
- **Weight**
- **Volume**
- **Board area**
- **Reliability**
- **Electrical performance**

Aluminum Electrolytic vs. Stacked Ceramics

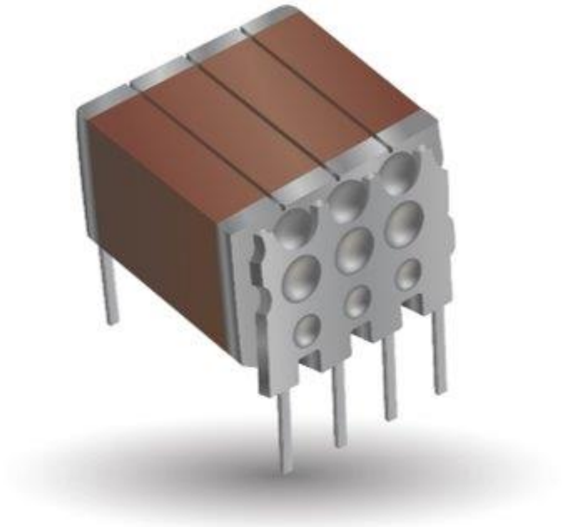
Radial Aluminum Electrolytic compared to Stacked Capacitor

Note – Multiple stacked capacitor types now exist:

Aluminum Electrolytic Cap



Horizontal stacks



Vertical stacks

Aluminum Electrolytic vs. Stacked Ceramics

Mechanical

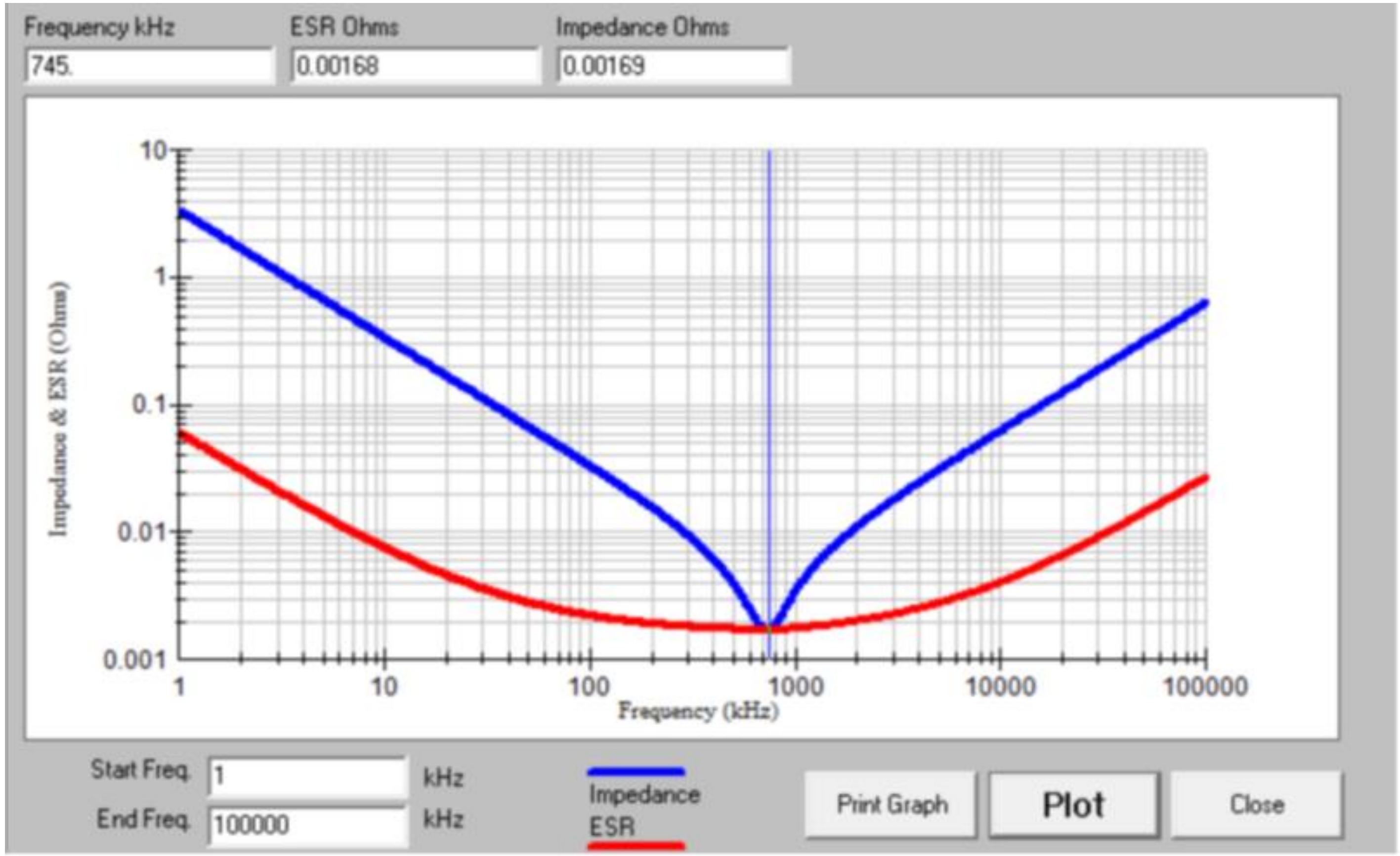
Radial Aluminum Electrolytic compared to Stacked Capacitor (in this study)

Parameter	Stacked Ceramic	Radial Electrolytic
Weight - grams	4.6	11.5
Volume - cubic mm	1463	7600
Board Area (X-Y) – square mm	217	211
Height - mm	6.75	36
Weight/uF - grams/uF	0.098	0.0035
Volume/uF - cubic mm/uF	31.13	2.30

Aluminum Electrolytic vs. Stacked Ceramics

Electrical

Stacked MLCC Frequency response



Aluminum Electrolytic vs. Stacked Ceramics

Electrical

Stacked MLCC
Frequency response

Typical ESR Performance (mΩ)

	Aluminum Electrolytic 100µF/50V	Low ESR Solid Tantalum 100µF/10V	Solid Aluminum Electrolytic 100µF/16V	MLCC SMPS 100µF/50V	MLCC SMPS 4.7µF/50V
ESR @ 10KHz	300	72	29	3	66
ESR @ 50KHz	285	67	22	2	23
ESR @ 100KHz	280	62	20	2.5	15
ESR @ 500KHz	265	56	18	4	8
ESR @ 1MHz	265	56	17	7	7.5
ESR @ 5MHz	335	72	17	12.5	8
ESR @ 10MHz	560	91	22	20	14

High Reliability Stacked Capacitor Specifications

- MIL PRF 49470/1
- MIL PRF 49470/2
- DSCC 87106
- DSCC 88011

Horizontal Stacked Ceramic Capacitor Reliability

PRODUCT: Horizontal Stacked MLCC - Multiple Case Sizes

TEST CONDITIONS: DATA BASED ON 1000 OR 2000 HOURS LIFE TESTING AT 200% RATED VOLTAGE AND 125ºC

		Max. Rated Voltage & Temperature (100% rated voltage, 125ºC)		Non-Standard Conditions (50% rated voltage, 50ºC)		
Product Type	**Lots Tested**	**Equivalent Device Hrs.**	**Failure Rate 1/**	**Equivalent Device Hrs.**	**Failure Rate 1/**	**Failure Rate (FITS**) 2/**
Horizontal Stacked - MLCC	98	1.43E+07	0.03	1.14E+11	0.000003	0.03

MTBF	2.94E+10

NOTES:

1/ FAILURE RATES ARE CALCULATED IN PERCENT PER 1000 HOURS AT 90% CONFIDENCE LEVEL

2/ 1 FIT = 1 FAILURE IN 10 E+9 HOURS AT 90% CONFIDENCE LEVEL (PPM/1000 hours)

Total Acceleration (Acc_T) = Temperature Acceleration (Acc_t) x Voltage Acceleration (Acc_V)

Where:

V_t = Test Voltage V_u = Use Voltage t_t = Test Temp. t_u = Use Temp.

$$Acc_V = \left(\frac{V_t}{V_u}\right)^3 \qquad Acc_t = 10^{\left(\frac{t_t - t_u}{25}\right)}$$

Vertical Stacked Ceramic Capacitor Reliability

PRODUCT: Vertical Stacked MLCC - Multiple Case Sizes

TEST CONDITIONS: DATA BASED ON 1000 OR 2000 HOURS LIFE TESTING AT 200% RATED VOLTAGE AND 125°C

Product Type	Lots Tested	Max. Rated Voltage & Temperature (100% rated voltage, 125°C) Equivalent Device Hrs.	Max. Rated Voltage & Temperature (100% rated voltage, 125°C) Failure Rate 1/	Non-Standard Conditions (50% rated voltage, 50°C) Equivalent Device Hrs.	Non-Standard Conditions (50% rated voltage, 50°C) Failure Rate 1/	Failure Rate (FITS**) 2/
Vertical Stacked - MLCC	98	1.43E+07	0.03	1.14E+11	0.000003	0.03

MTBF	2.94E+10

NOTES:

1/ FAILURE RATES ARE CALCULATED IN PERCENT PER 1000 HOURS AT 90% CONFIDENCE LEVEL

2/ 1 FIT = 1 FAILURE IN 10 E+9 HOURS AT 90% CONFIDENCE LEVEL (PPM/1000 hours)

Total Acceleration (Acc_T) = Temperature Acceleration (Acc_t) x Voltage Acceleration (Acc_V)

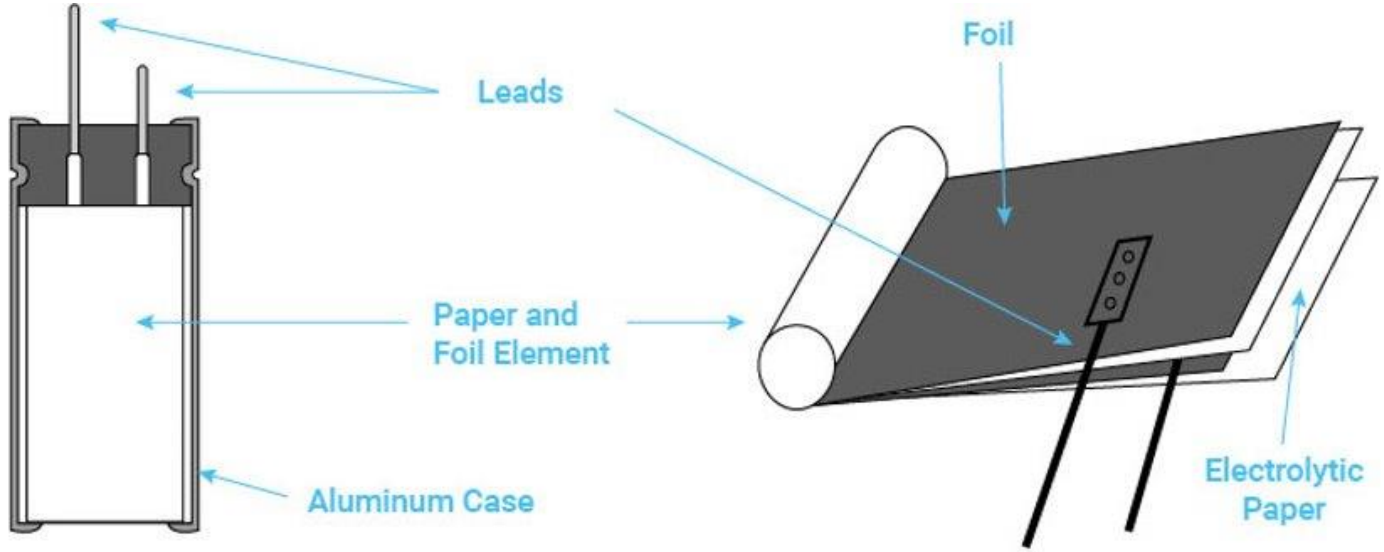
Where:

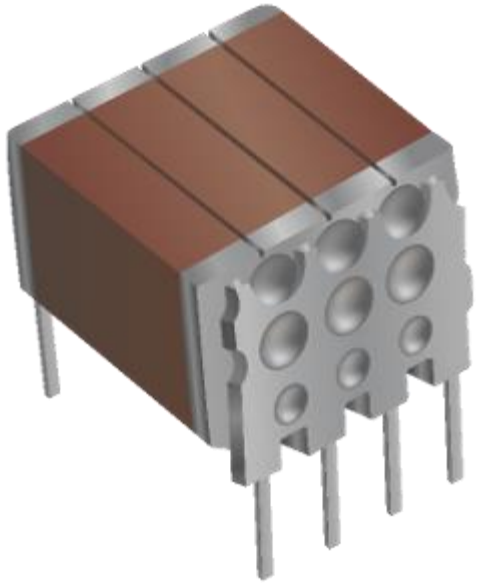
V_t = Test Voltage V_u = Use Voltage t_t = Test Temp. t_u = Use Temp.

$$Acc_V = \left(\frac{Vt}{Vu}\right)^3 \qquad Acc_t = 10^{\left(\frac{t_t - t_u}{25}\right)}$$

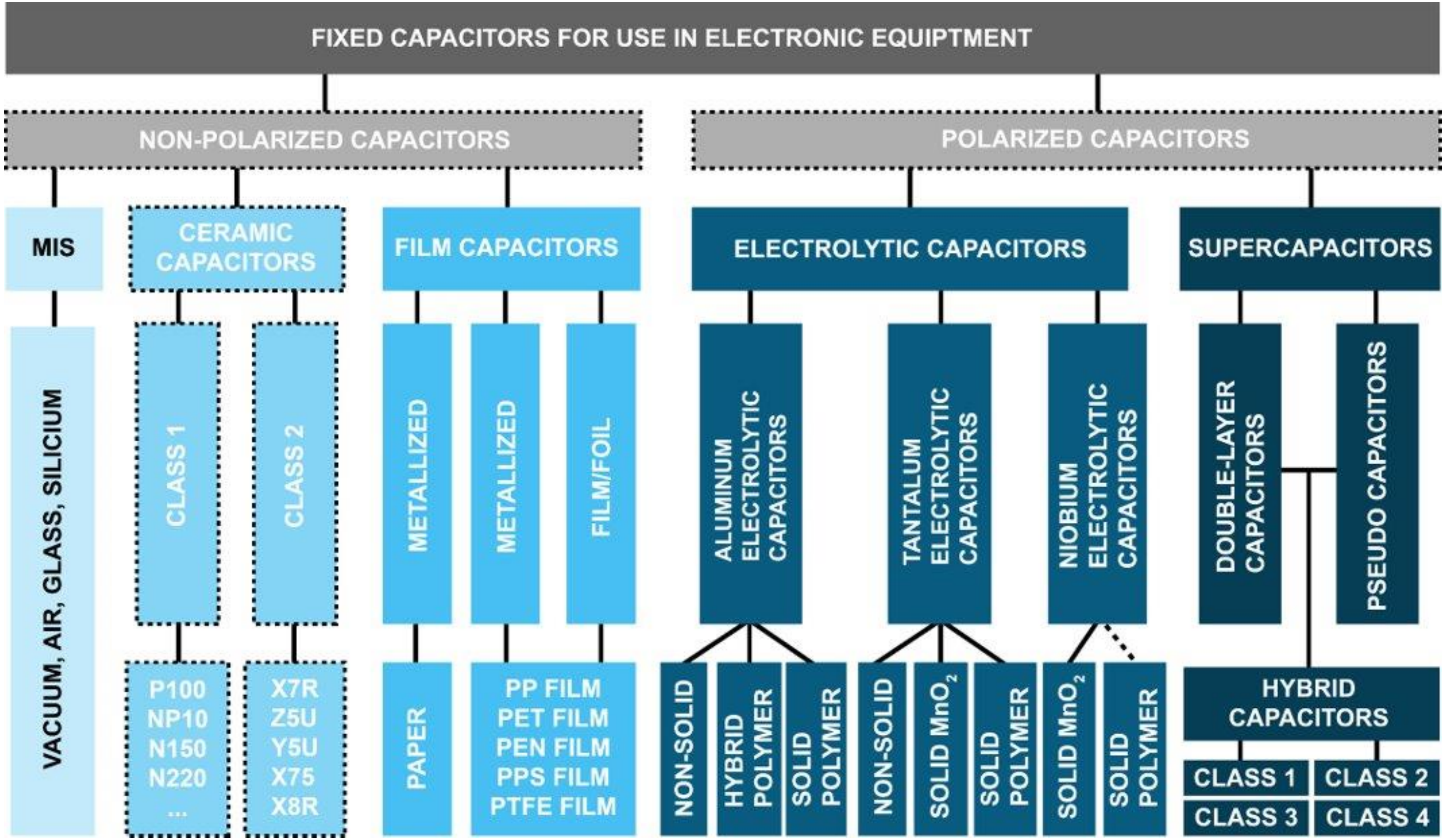
General Capacitor Selection Rules

Lowered Inductance





Recap

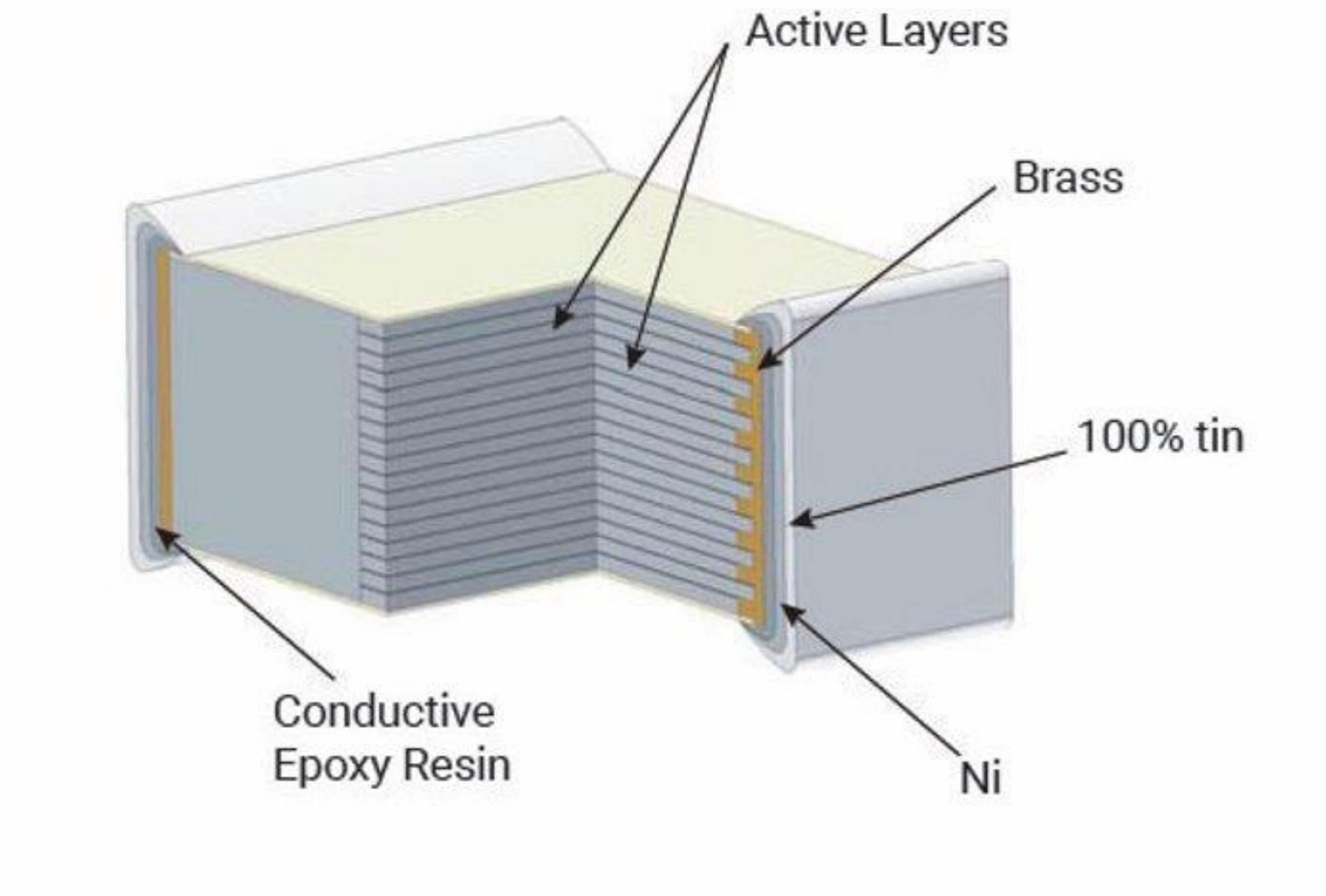


FIXED CAPACITORS FOR USE IN ELECTRONIC EQUIPTMENT
NON-POLARIZED CAPACITORS
POLARIZED CAPACITORS
MIS
CERAMIC CAPACITORS
FILM CAPACITORS
ELECTROLYTIC CAPACITORS
SUPERCAPACITORS
VACUUM, AIR, GLASS, SILICIUM
CLASS 1
CLASS 2
METALLIZED
METALLIZED
FILM/FOIL
ALUMINUM ELECTROLYTIC CAPACITORS
TANTALUM ELECTROLYTIC CAPACITORS
NIOBIUM ELECTROLYTIC CAPACITORS
DOUBLE-LAYER CAPACITORS
PSEUDO CAPACITORS
P100 NP10 N150 N220 ...
X7R Z5U Y5U X75 X8R
PAPER
PP FILM PET FILM PEN FILM PPS FILM PTFE FILM
NON-SOLID
HYBRID POLYMER
SOLID POLYMER
NON-SOLID
SOLID MnO_2
SOLID POLYMER
SOLID MnO_2
SOLID POLYMER
HYBRID CAPACITORS
CLASS 1
CLASS 2
CLASS 3
CLASS 4

Film Capacitors

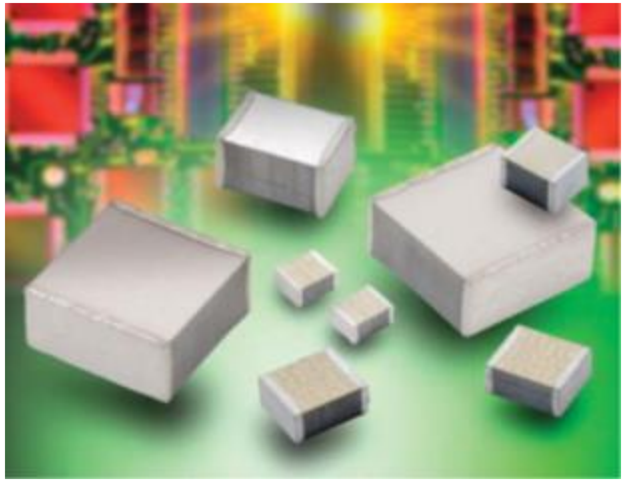
Electrostatic Capacitors - Film

FAILSAFE – Does not short



- Fixed Value
- Ceramic is the dielectric
- Metal is the electrode
- Multiple layers
- Various shapes/forms

Stacked Film Capacitors (Common examples)

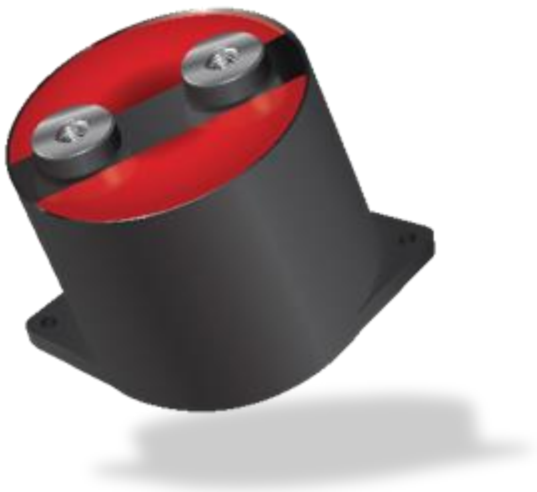


- Low inductance
- No noise
- Self healing
- High Thermal shock capability
- High Temperature Cycle capability

PPS (Polyphenylene sulfide)	PET (Polyethylene tetraphtalate)	PEN (Polyethylene Napthalate)
-55c to 125c	-55c to 125c	-55c to 125c
1206, 1210, 1812	1206 to 6054	1206 to 6054
1nf – 180 uf	10nf to >>>4.7 uf	1nf to 4.7uf
2% 5% 10%	5% 10%	5% 10%
16v to 50v	63v to 630v	25v to 630v

Assembly

1. Stamping/labeling
2. Special testing and screening :
   - Thermal cycle/shock
   - DC elevated temp burn-in
   - AC elevated temp burn-in
   - Power testing and thermal profiling
   - Specialized testing such as ramp testing, square wave, shock, vibration, humidity, pulsing/strobe
3. Testing to final print specifications
4. QC inspection to mechanical and point electrical requirements

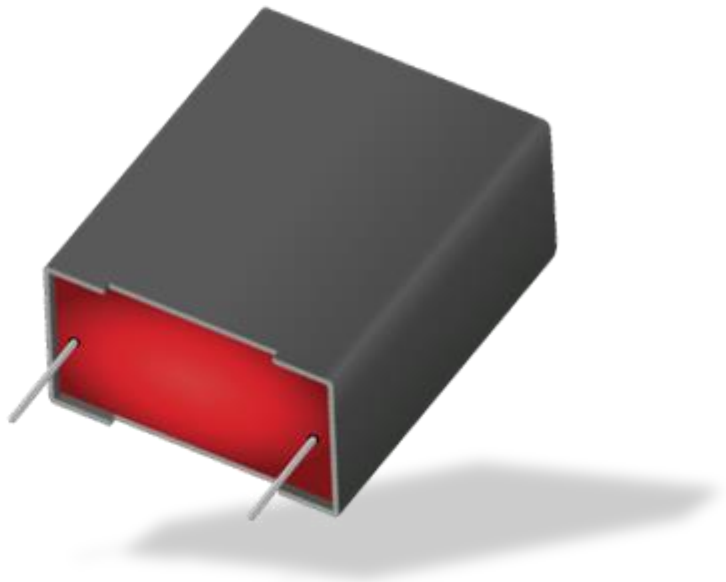


Testing

All capacitors are tested at least twice for standard parameters:

- Dielectric withstanding voltage (DWV)
- Capacitance
- Dissipation factor (DF)
- Equivalent Series Resistance (ESR)
- Insulation Resistance (IR)

Specific tests as specified by the customer

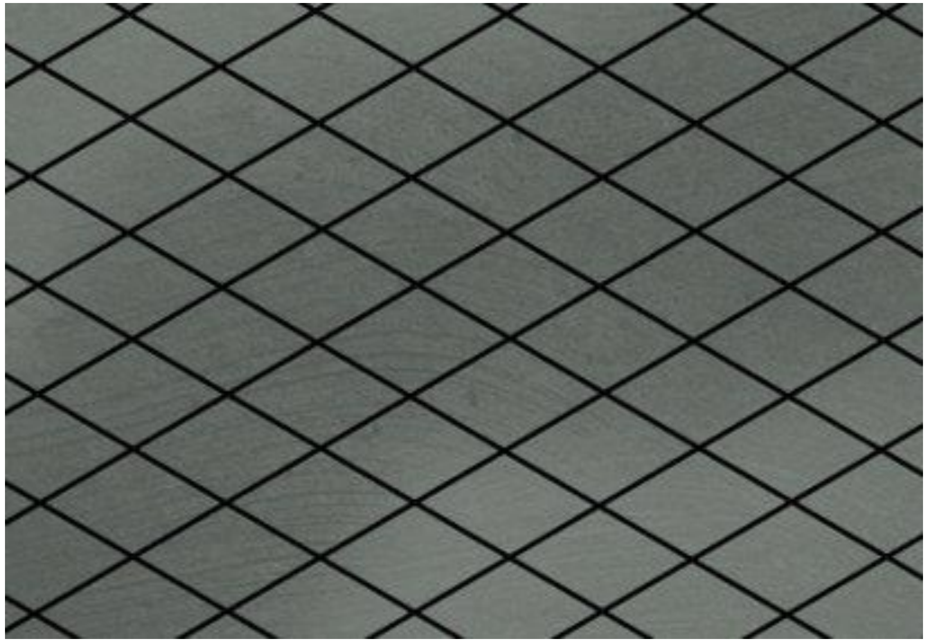


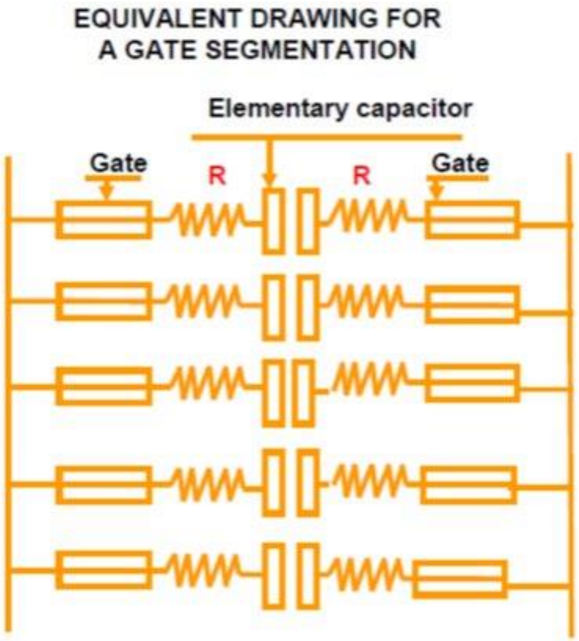
Metalized Film

Film is Metalized in a Specific Pattern to Create Small Fused Areas

Careful –

Manufacturers have different fusing methods – therefore different wear out rates





Metalized Film

Metallized Film is Wound Into Pucks, Bobbins, and Dice-able SMT Chips

Basic Concept: development, qualification and production of standard elementary wound bobbins.

Flat Bobbin

- Film Width: ½'' up to 6''
- Thickness: up to 1.6''
- Length: up to 7''

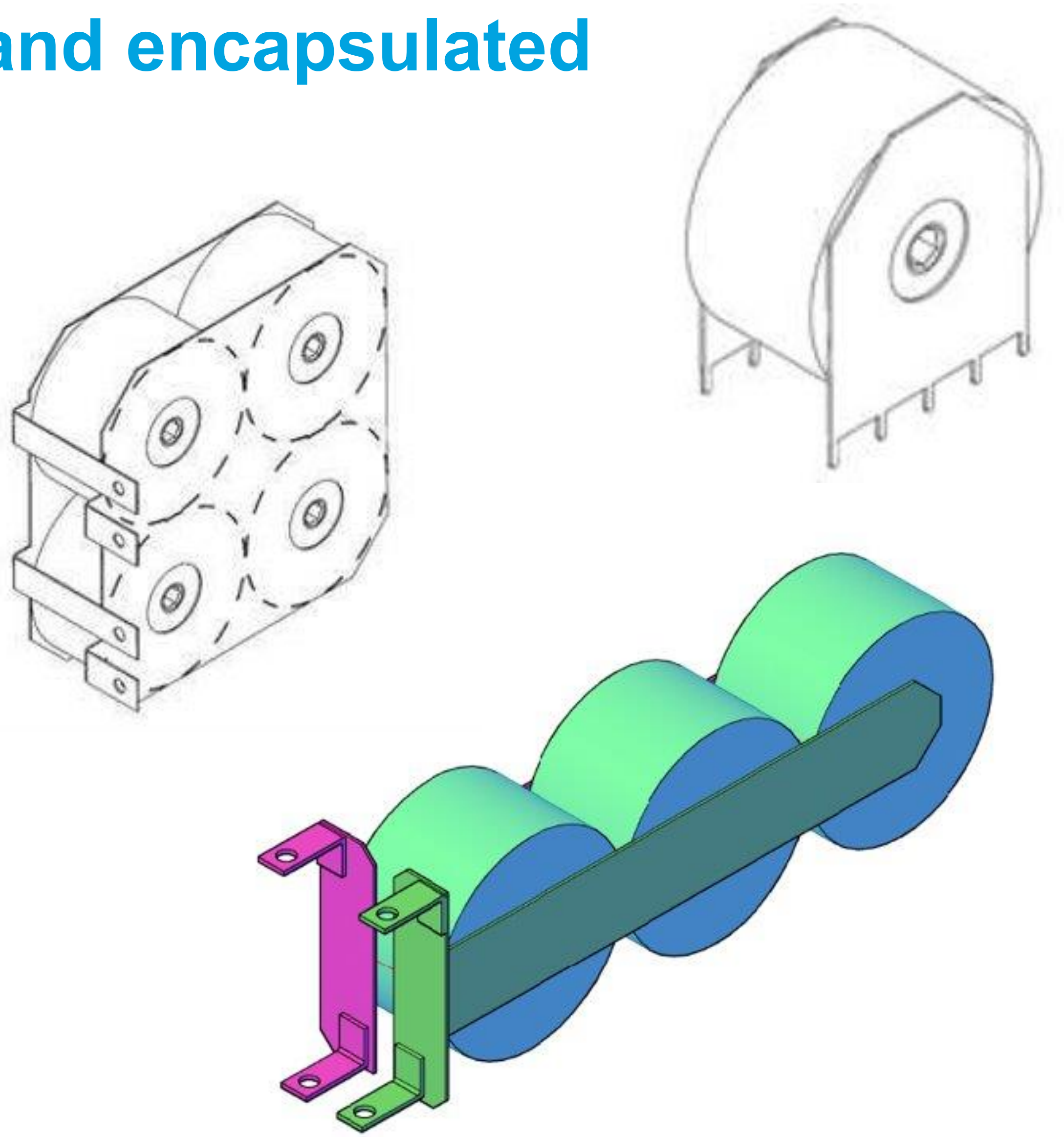
Cylindrical "Puck" Shape

- Film Width: ½'' up to 6''
- External diameter up to 3.2''

Puck

Pucks are placed onto bus bars and encapsulated

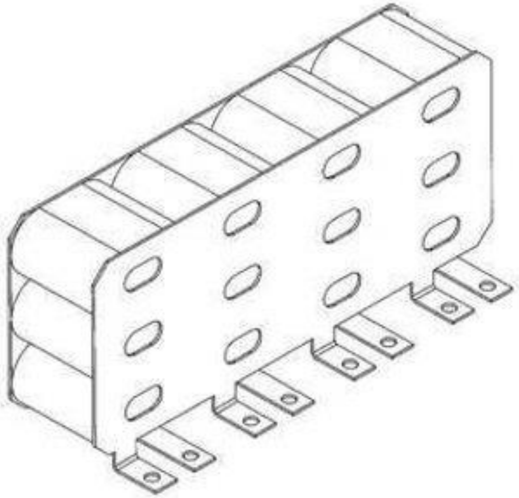
Fundamental brick to create modules

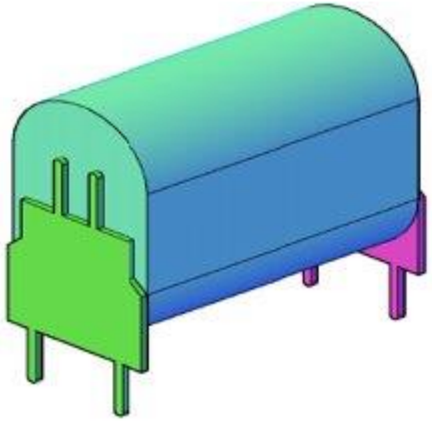


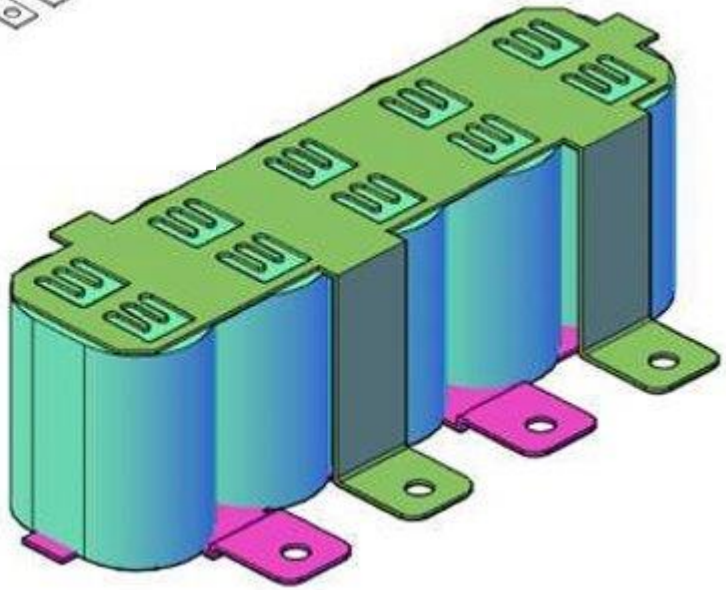
Bobbins

Bobbins are placed onto bus bars and encapsulated

Fundamental brick to create modules







Oil and Power Film Capacitors

Dry

- Metallized film, segmented
- Cylindrical or flat and hard bobbins
- Resin filled case

No Free Oil

- Metallized film with organic oil between layers, non-segmented
- Flat and soft bobbins
- Resin filled case

Oil Impregnated

- Metallized film, Rapeseed oil impregnated, non-segmented
- Flat and soft bobbins
- Oil filled case

Characteristics of Film SMD Capacitors

Temperature
DC Bias
Time
Frequency

	PET (MKT)	PEN (MKN)	PPS (MKI)	NPO	X7R	Tantalum
Operating temperature (°C)	-55/125	-55/125	-55/140	-55/125	-55/125	-55/125
⊗C/Cwith temperature (%)	+/- 5	+/- 5	+/- 1.5	+/- 1	+/- 15	+/- 10
DC voltage coefficient (%)	negl.	negl.	negl.	negl.	-20	negl.
⊗C aging rate (%/h dec.)	negl.	negl.	negl.	negl.	2	n.a.
Dissipation factor (%) 1 kHz 10 kHz 100 kHz	 0.8 1.5 3.0	 0.8 1.5 3.0	 0.2 0.25 0.5	 0.10 0.10 0.10	 2.5	 8
ESR	low	low	very low	low	moderate to high	high
IR (M· . µF) 25°C 85°C	 10000 1000	 10000 1000	 10000 1000	 10000 1000	 1000 500	 100 10
Dielectric absorption (%)	0.5	1	0.05	0.6	2.5	n.a.
Capacitance range from (pF) to (µF)	1000 10	1000 4.7	100 1	10 0.047	100 4.7	100000 1000
Capacitance tolerance (+/- %)	5 10 20	5 10 20	2.5 5 10 20	5 10	10 20	10 20
Self healing	yes	yes	yes	no	no	no
Typical failure mode at end of life	open	open	open	short	short	short
Reliability	high	high	high	high	moderate	low
Piezoelectric effect	no	no	no	yes	yes	yes
Resistance to thermal and Mechanical shock	high	high	high	moderate to low	moderate to low	high
Non-linear distorsion (3^{rd} harmonic)	very low	very low	very low	low	high	n.a.
Polarity	no	no	no	no	no	yes

[1] All data are typical values

N.B. : SMD = Surface Mounted Device
SMT = Surface Mounted Technology

Common Film Types:

Polypropylene (PP)

Polyphenylene Sulfide (PPS)

Polycarbonate (PC)

Polyethylene Naphthalate (PEN)

Teflon (PTFE)

Polyethylene terephthalate (PET)

Why use Film Capacitors?

Advantages of Film Dielectric

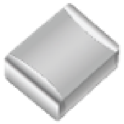
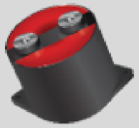
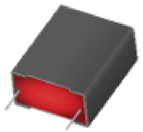
- Self Healing property, Open failure mode
- Low dissipation factor, ESR and ESL
- Excellent thermal shock resistance
- No piezoelectric effect
- Non polar construction
- No derating vs voltage or temperature (good stability)
- Good capacitance/volume ratio due to stacked construction
- Competitive vs. ceramic high voltage or high capacitance values

Why use Film Capacitors?

Electrolytic Alternate

	FILM	ELECTROLYTIC
SURGE VOLTAGE	2X RATED VOLTAGE	1.2 X RATED VOLTAGE
REVERSE VOLTAGE ALLOWED	YES	NO
RMS. CURRENT	UP TO 1ARMS PER µF	0.025 ARMS PER µF
MTBF	10M HOURS	1M HOURS
LIFE TIME	>100,000H	40,000H
STORAGE	> 10 YEARS	1 YEAR MAX
ENVIRONMENTALLY FRIENDLY	YES	NO
END OF LIFE	SOFT – 15% CAP LOSS	EXPLOSION RISK

Film Capacitor Applications

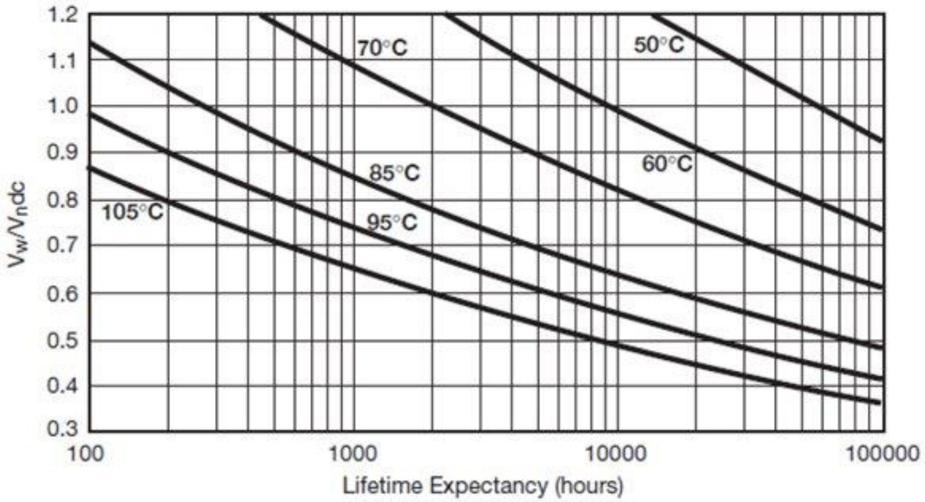
FILM CAPACITOR			APPLICATIONS						
			AUTOMOTIVE	CONSUMER	LIGHTING	MEDICAL	NEW ENERGY	POWER	TELECOM/ DATA
SMD CAPACITOR		**PET Dielectric & PPS Dielectric:** Good for Blocking/Coupling, Bypass, Decoupling, and Smoothing.	X	X		X		X	X
FILM CAPACITOR		**PET/PP – Metallized** **Film:** Blocking/Coupling, Bypass/Decoupling, **Film/Foil:** Band-pass Filter, Band stop Frequencies, Timing, Peak Voltage Detectors.	X	X	X	X		X	X
EMI SUPPRESSION CAPACITOR		**Metallized Paper:** Dielectric-suppresses High-frequency Disturbances of Electrical Equipment on the Mains. Capacitor Voltage Dropper.		X	X	X	X	X	X
PULSE DUTY CAPACITOR		**PP Dielectric:** High pulse duty. Smoothing, energy Storage, Oscillating Circuit, Snubbing (Relay).	X	X	X	X		X	X
GTO CAPACITOR		**Energy Storage:** stores the energy and releases in a short time. Snubbing (GTO Thyristor)-decreases over voltage peaks by high current switching.					X	X	
DC-LINK CAPACITOR		**Energy Buffer:** (converter) - Capacitor stores DC-voltage in an intermediate circuit. Non-Polar.	X				X	X	
SNUBBER CAPACITOR		**Energy Storage:** Capacitor is charged to a high voltage, stores the energy and releases it in a short time. **Snubbing:** (IGBT) low-self inductance.	X	X		X	X	X	

Power Film Capacitor

Lifetime Calculation

Calculations

LIFE TIME EXPECTANCY vs VOLTAGE & HOT SPOT TEMPERATURE



Hot spot temperature will be determined with the following expression:

$$\theta max_{hotspot} = \theta_{ambient} + I^2_{rms} \times \left[rs + \frac{1}{C \times 2 \times \pi} \times tg\delta_0 \right] \times Rth$$

with: $\theta max_{hotspot}$: the maximum hot spot temperature

$tg\delta_0$: dielectric losses

Rth: Thermal resistance

Rs: Serial resistance

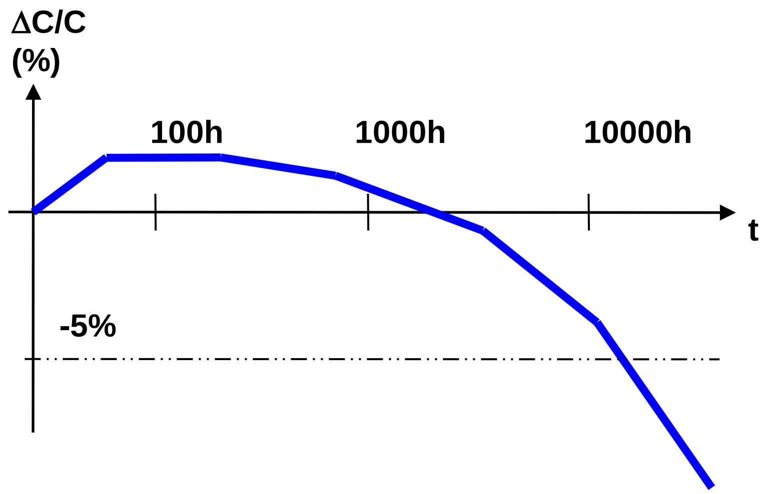
θhot spot will be 85°C or 105°C function of the application and the technology.

Controlled Self-Healing

Medium Voltage Power Technology:

Basic concept of segmented metallized film:

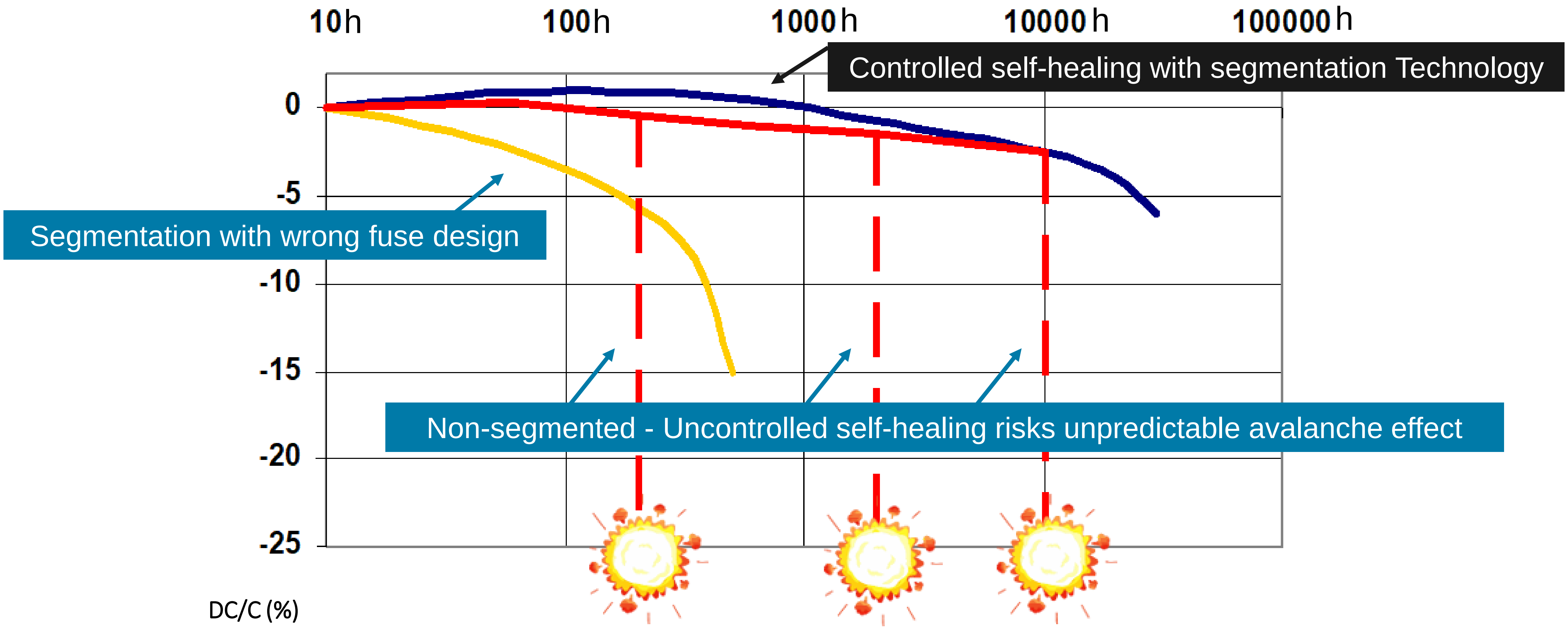
- The total capacitance is divided into elementary cells protected by fuse gates (several million).
- In the event of a weak point, only that cell will be removed by fuse activation.
- Capacitance decreases as a function of cell element fuse activation.
- No catastrophic failure (short circuit) results, only a decrease in bulk capacitance.
- Aging level (Delta cap) is calculable.



→ **Total Safety**

Careful

Controlled Self-Healing performance varies by mfgr



Lifetime: Mission Profile

Mission profile Input data: I, ambient temp, voltage are given vs rate

RATE	3%	7%	18%	32%	24%	10%	5%	1%
I (ARMS)	50	190	250	220	200	150	120	100
POWER (W)	5	8	12.5	9.7	8	4.5	3	2
AMB TEMP.	76	79	83	92	100	116	134	138
$\Delta\theta$ (°C)	5	8	10	9	8	5	3	2
HOT SPOT (°C)	81	87	93	101	108	121	137	140
VOLTAGE (V)	600	550	500	490	460	375	315	280

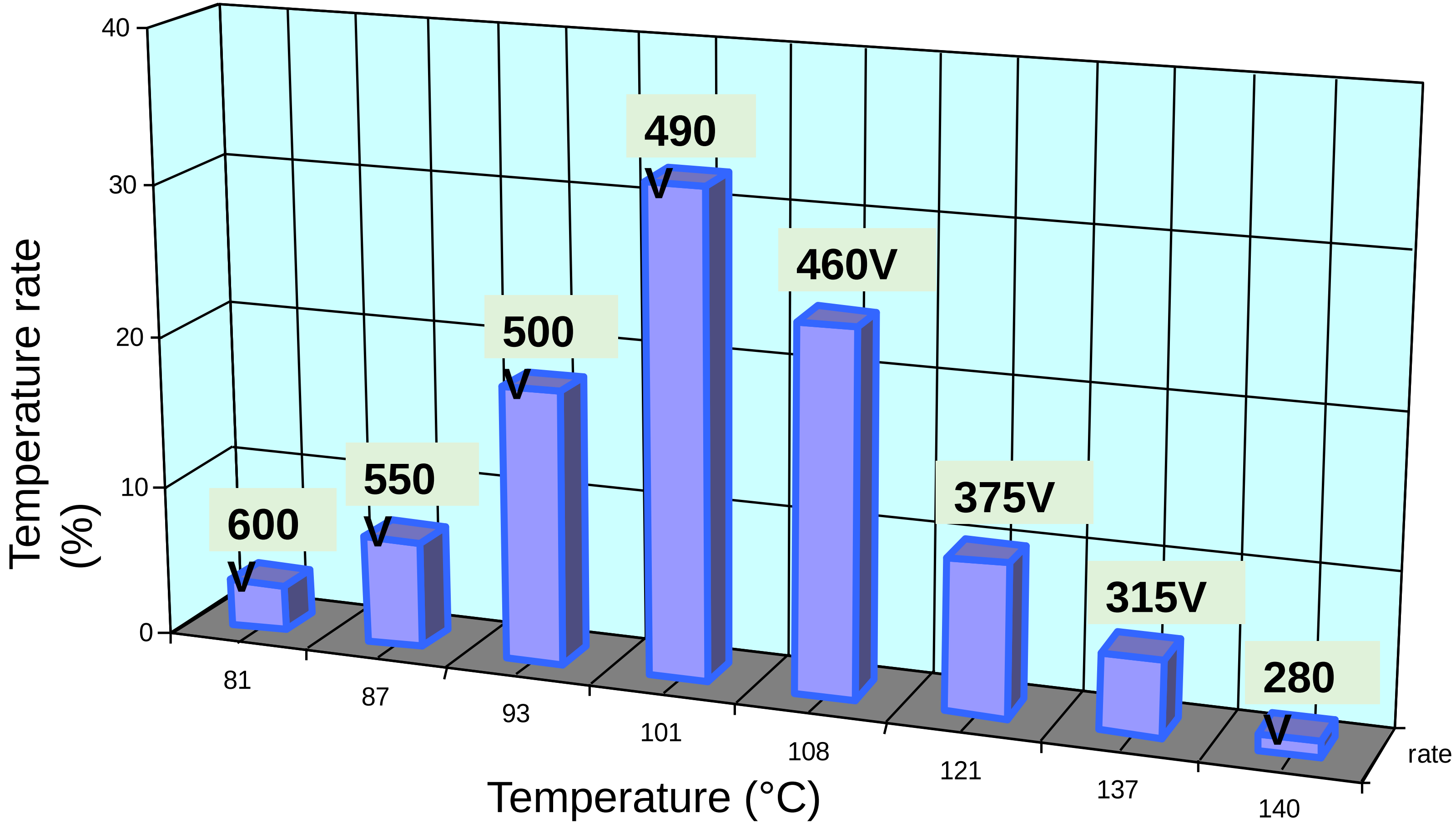
For each rate, lifetime consumption is calculated vs voltage and Hot Spot temperature

Lifetime: Mission Profile

Lifetime Expectancy:

$$\frac{13\ 000h}{\sum Lci} = 20\ 000h$$

(Σ Lci=65%)



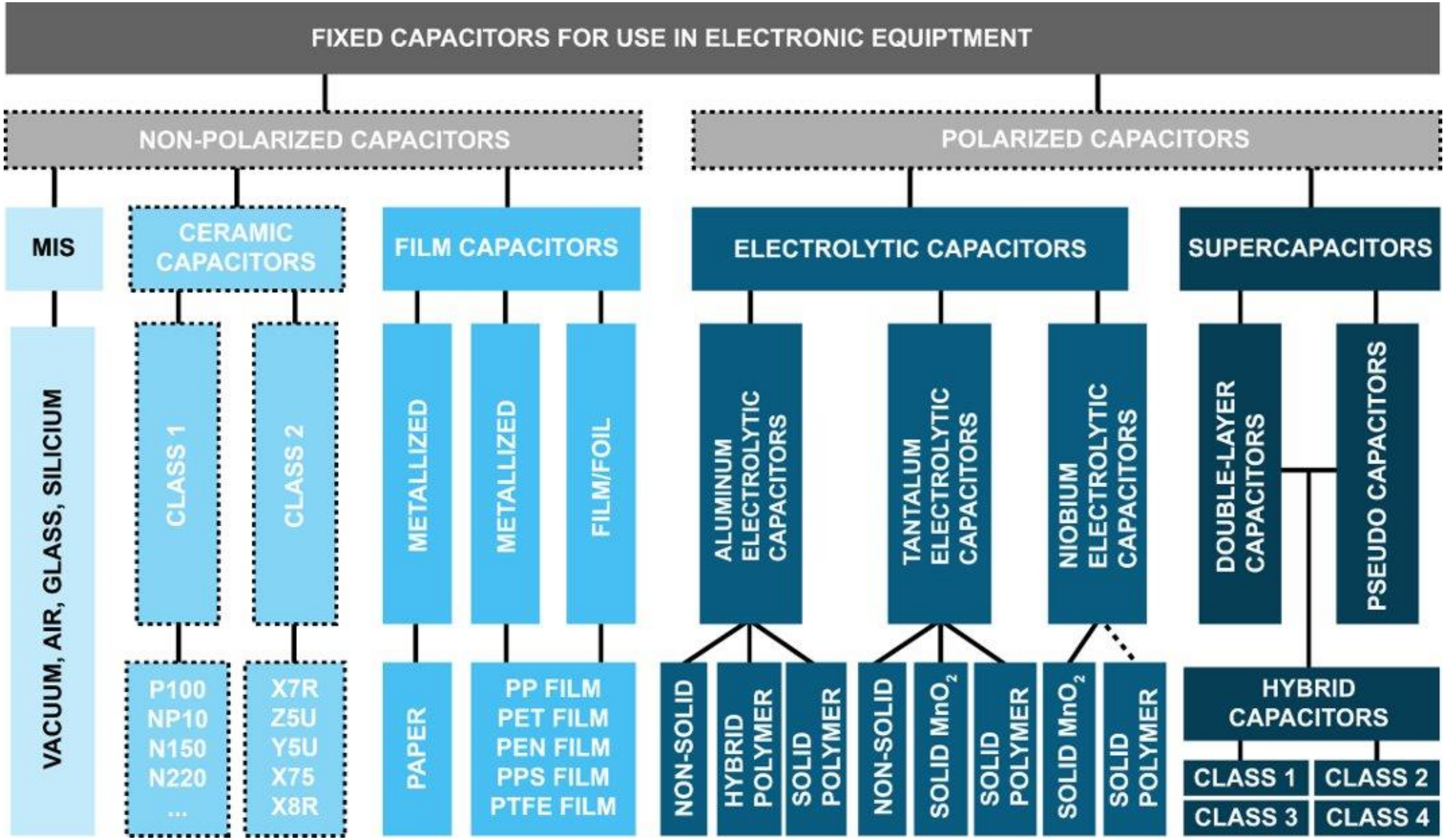
LIFETIME CON SUMPTION (LC)	2%	2%	6%	9%	8%	3%	32%	3%

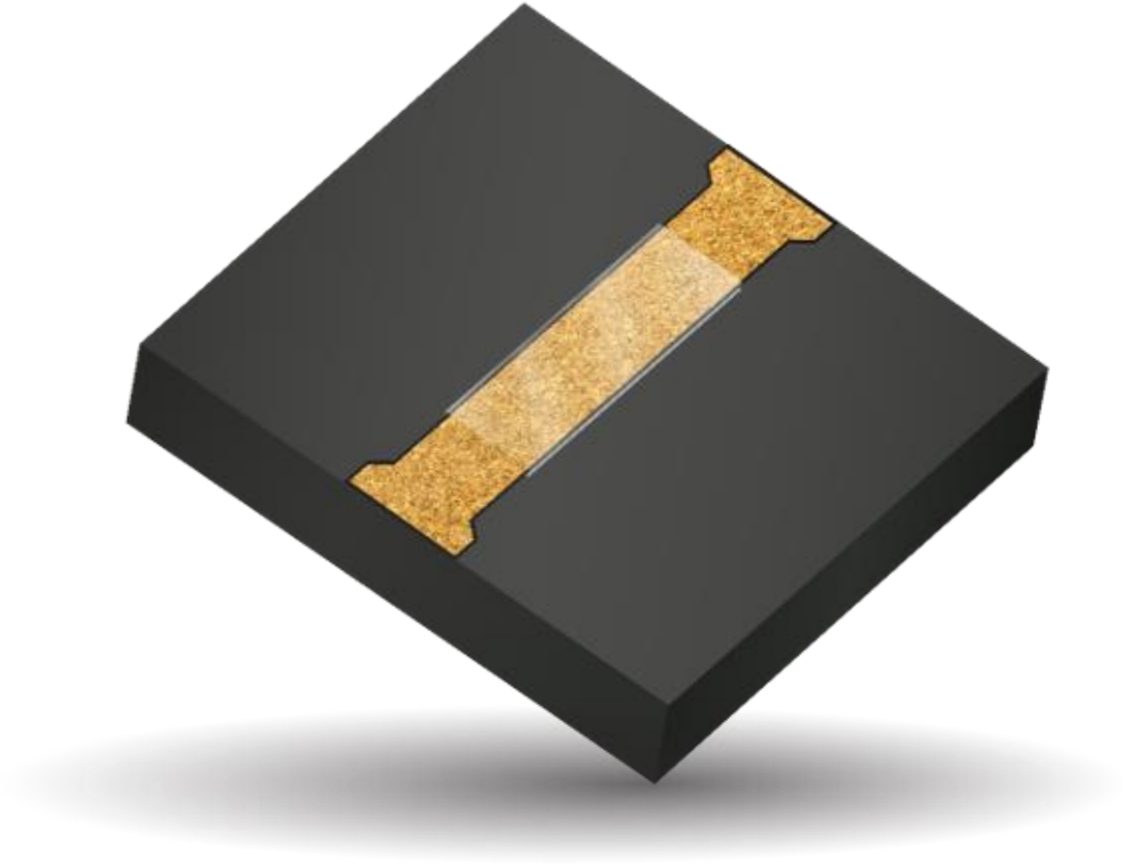
Design vs. Mission Profile

What correct design & use yields

Number of parts in use:	$3.01x\ 10^6$
Study period:	1979 - 2019
Number of different designs:	450
Voltage Range:	75v To 4.6kv
Estimation of Working Time:	66.3 Billion Hours
Catastrophic Failure:	ZERO

Recap


FIXED CAPACITORS FOR USE IN ELECTRONIC EQUIPTMENT
NON-POLARIZED CAPACITORS
POLARIZED CAPACITORS
MIS
CERAMIC CAPACITORS
FILM CAPACITORS
ELECTROLYTIC CAPACITORS
SUPERCAPACITORS
VACUUM, AIR, GLASS, SILICIUM
CLASS 1
CLASS 2
METALLIZED
METALLIZED
FILM/FOIL
ALUMINUM ELECTROLYTIC CAPACITORS
TANTALUM ELECTROLYTIC CAPACITORS
NIOBIUM ELECTROLYTIC CAPACITORS
DOUBLE-LAYER CAPACITORS
PSEUDO CAPACITORS
P100 NP10 N150 N220 ...
X7R Z5U Y5U X75 X8R
PAPER
PP FILM PET FILM PEN FILM PPS FILM PTFE FILM
NON-SOLID
HYBRID POLYMER
SOLID POLYMER
NON-SOLID
SOLID MnO_2
SOLID POLYMER
SOLID MnO_2
SOLID POLYMER
HYBRID CAPACITORS
CLASS 1
CLASS 2
CLASS 3
CLASS 4

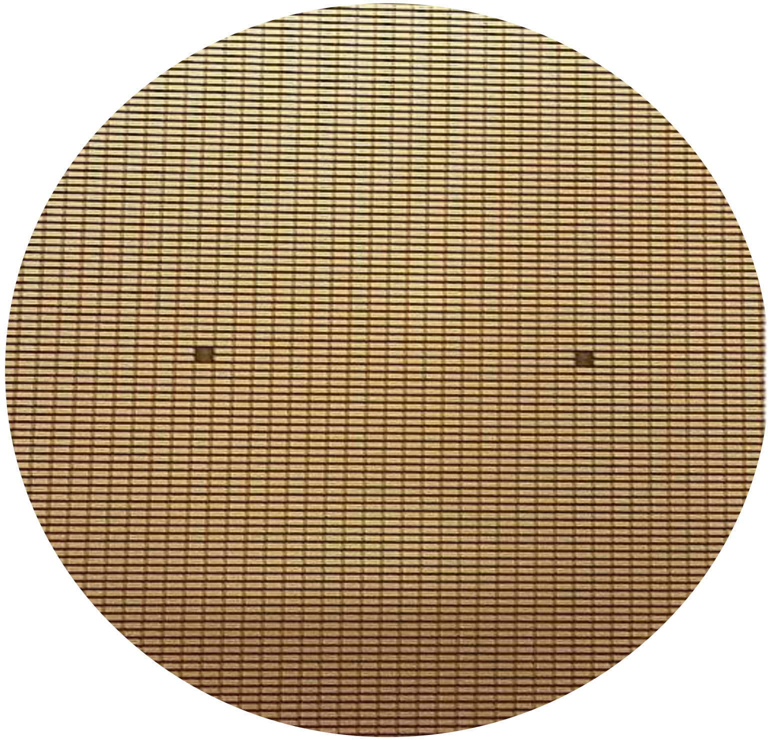


Thin Film Capacitors

Electrostatic Capacitors

Thin Film Capacitor

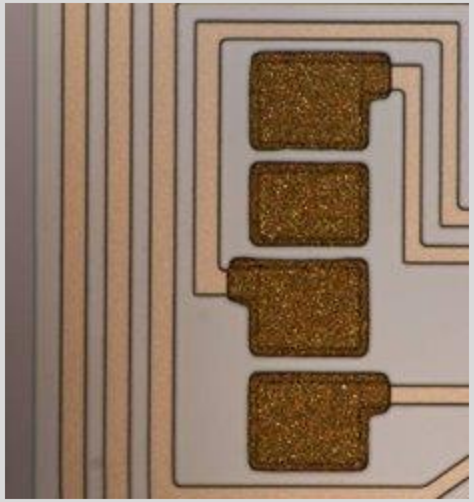
- Fixed Value
- Thin Film – SiO_2 Common dielectric
- Gold, Aluminum are common electrodes
- Single or multiple layer
- Various termination options



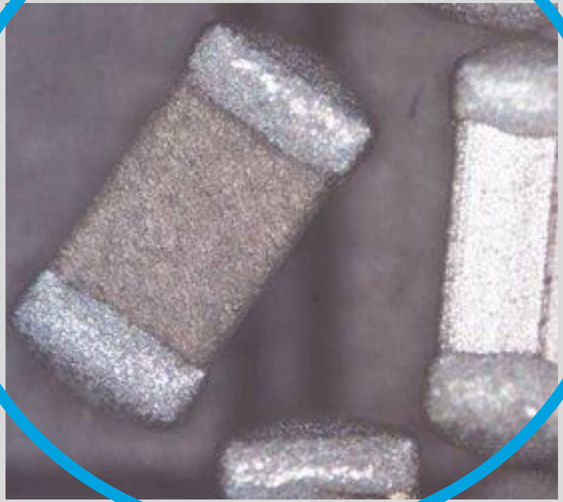
SiO_2 Dielectric

Thin Film Capacitor Types & Terminations

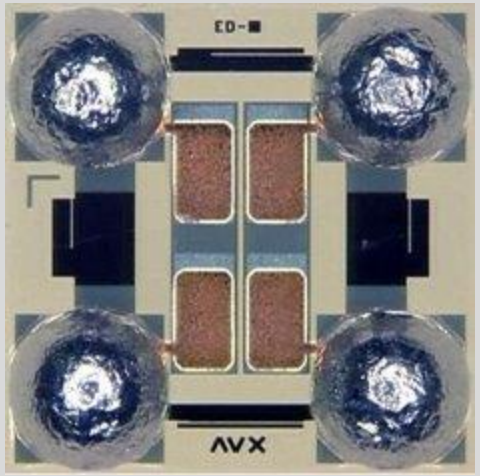
Au Wire-bond



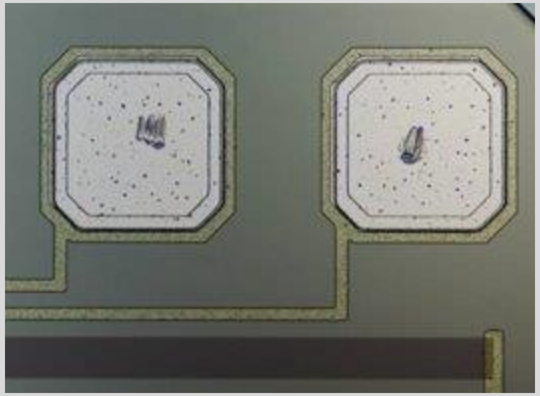
Surface Mount



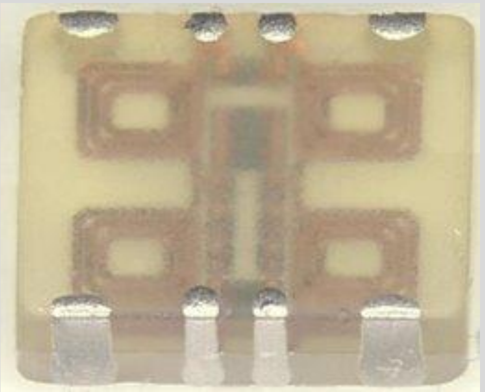
Ball Grid Array



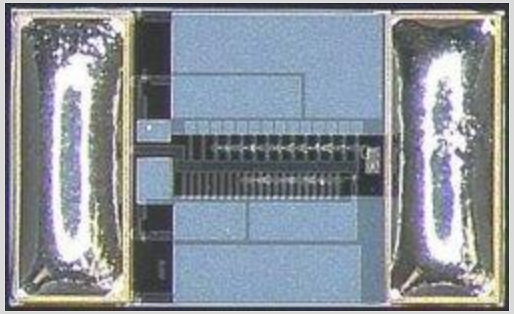
Al Wire-bond



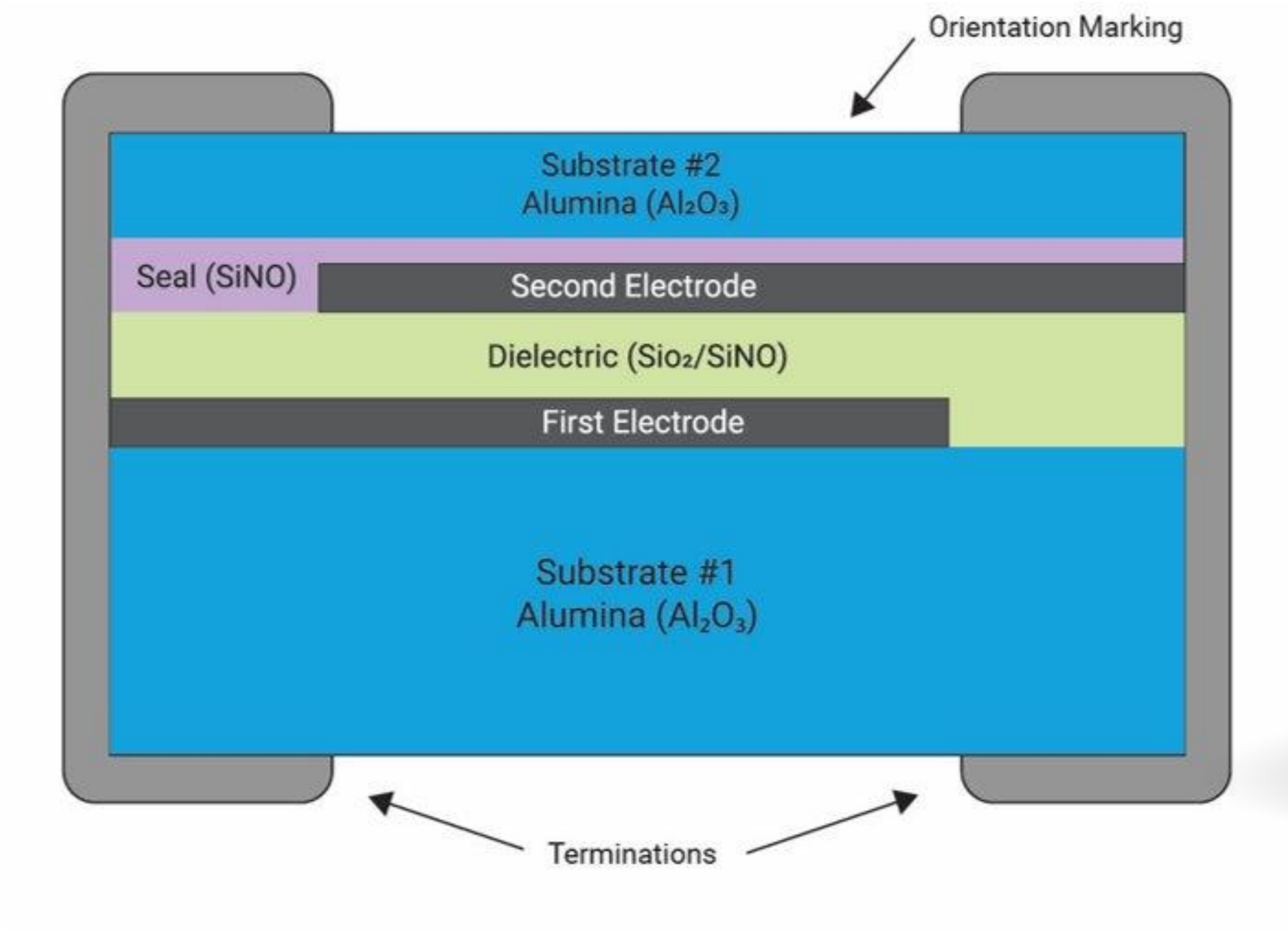
Surface Mount Array

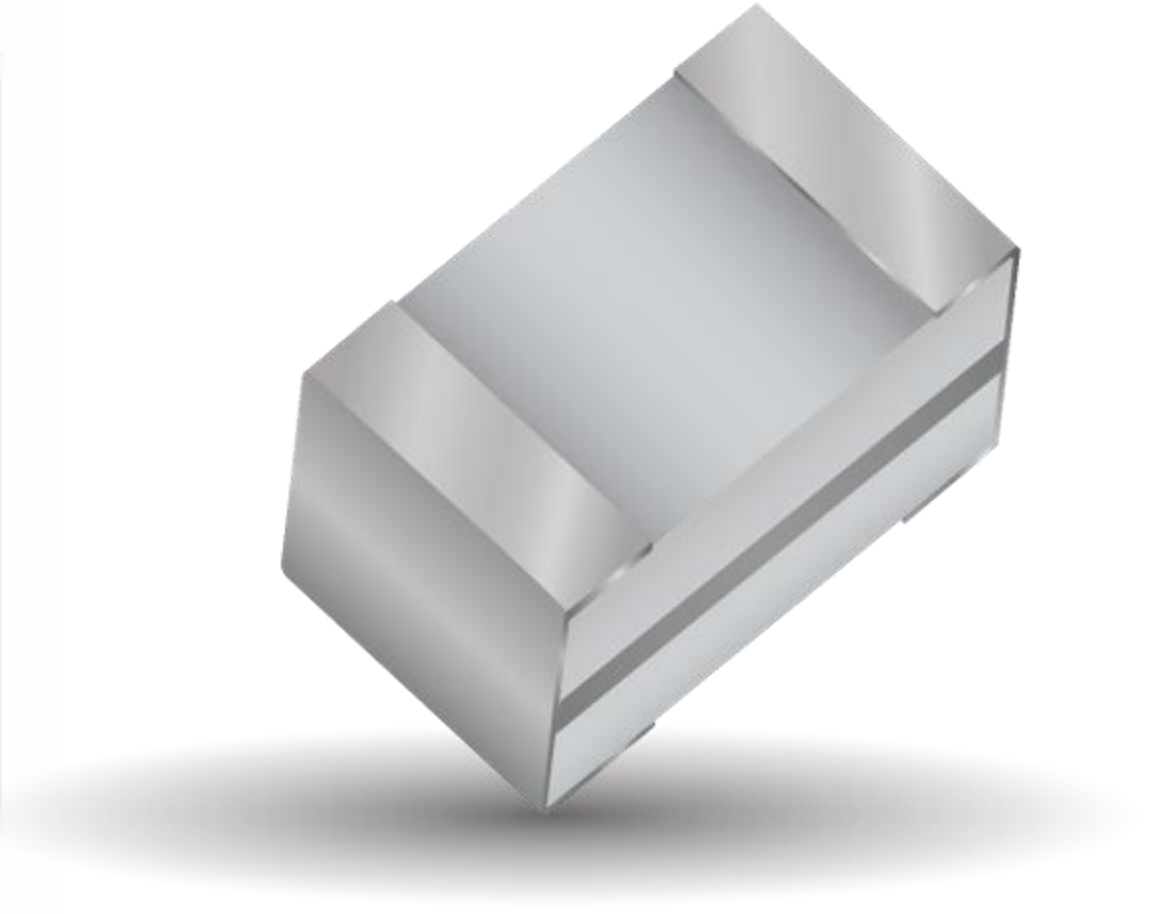


Land Grid Array



Final Product





Thin Film Capacitor

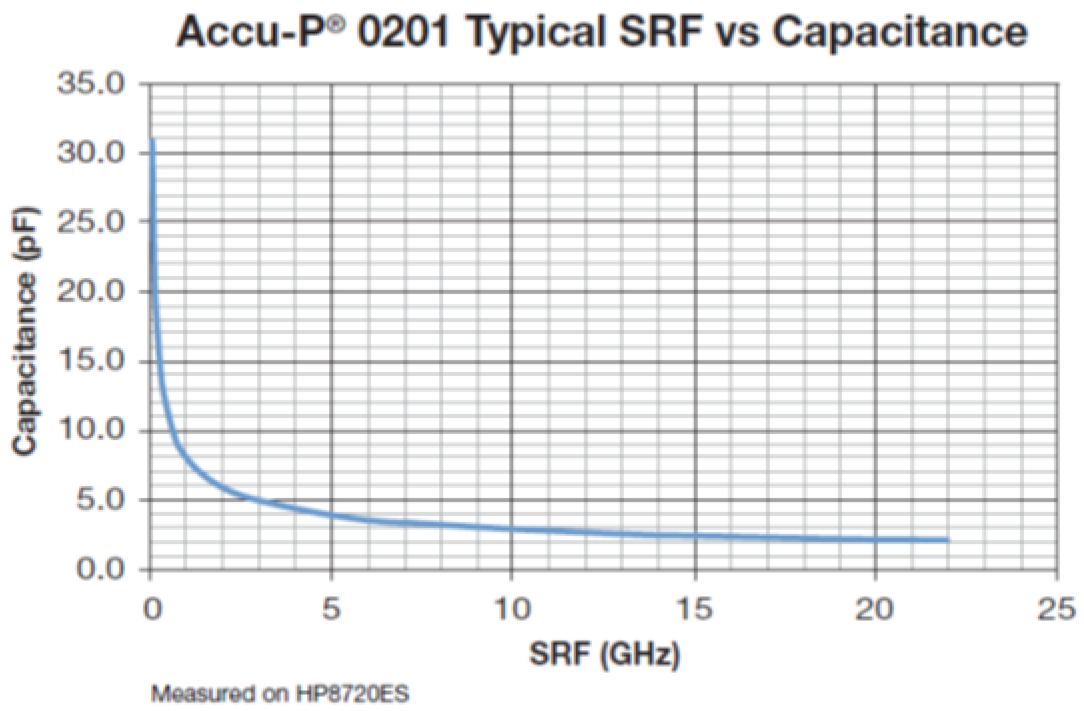
Exceptional capacitance tolerance, matching & stability

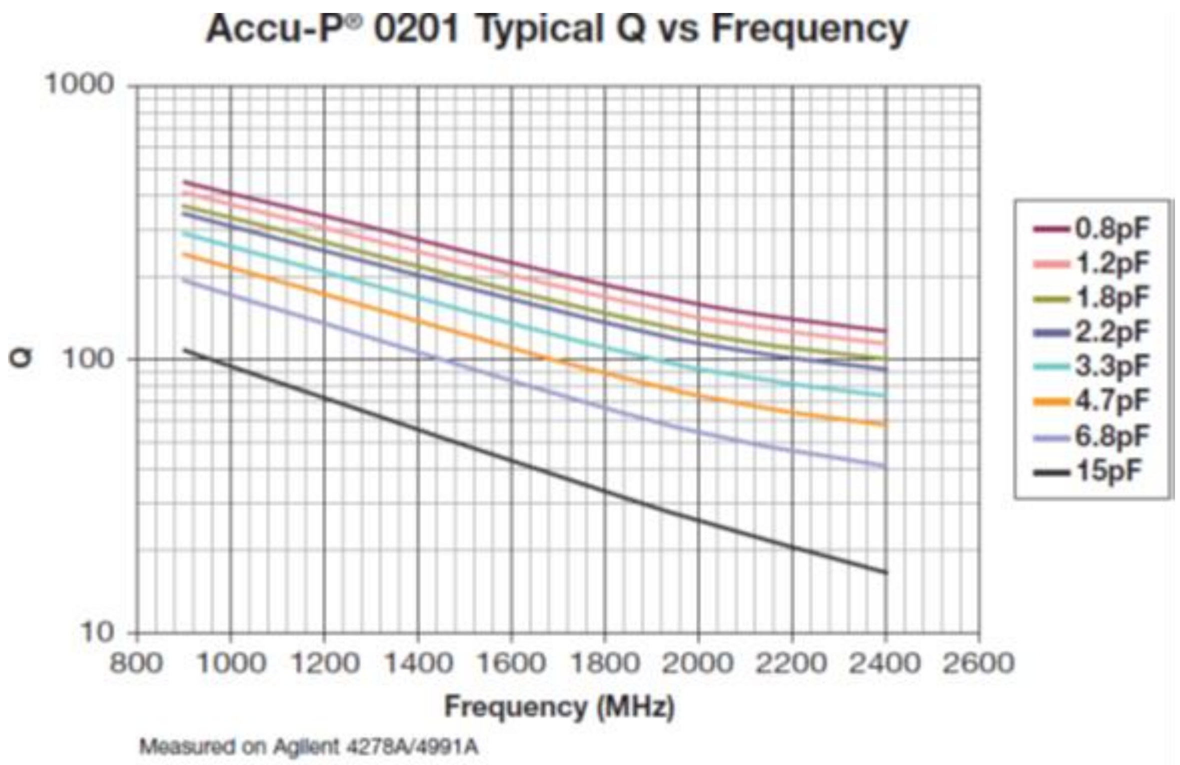
Time: Negligible Aging

Temperature: 0±30ppm/°C, 0±60ppm/°C

Voltage: Negligible DC bias effects

Frequency: exceptionally high Q and stable





Thin Film

Application

- RF & High Frequency, High precision
- **Value Range** – Sub Pf to < 100pf
- **Voltage range** </=200v
- **Tolerances** as tight as 10 fF / 0.01pf
- **Dielectric Absorption** </= 0.01%

Capacitor	Thermal Exchange in Degrees Celsius per Watt	Power Rating @ 20°C Rise above an ambient of 25°C
Thin Film Alumina Substrate 1210	59° C/Watt	.34 Watts
Thin Film Alumina Substrate 0805	83.3° C/Watt	.24 Watts
Thin Film Alumina Substrate 0603	106° C/Watt	.186 Watts
Thin Film Alumina Substrate 0402	158° C/Watt	.127 Watts
Procelain 0505	126° C/Watt	.158 Watts
Procelain 1111	67.7° C/Watt	.295 Watts
Ceramic 1210	70.9° C/Watt	.282 Watts
Ceramic 0805	113° C/Watt	.177 Watts
Ceramic 0603	145° C/Watt	.139 Watts
Ceramic 0402	219° C/Watt	.091 Watts

Thin Film Capacitor Reliability

Product : Thin Film 0402 Capacitor Reliability example (snap shot in time)

Test Conditions: 2xRated Voltage, 125°C, 1000 hours

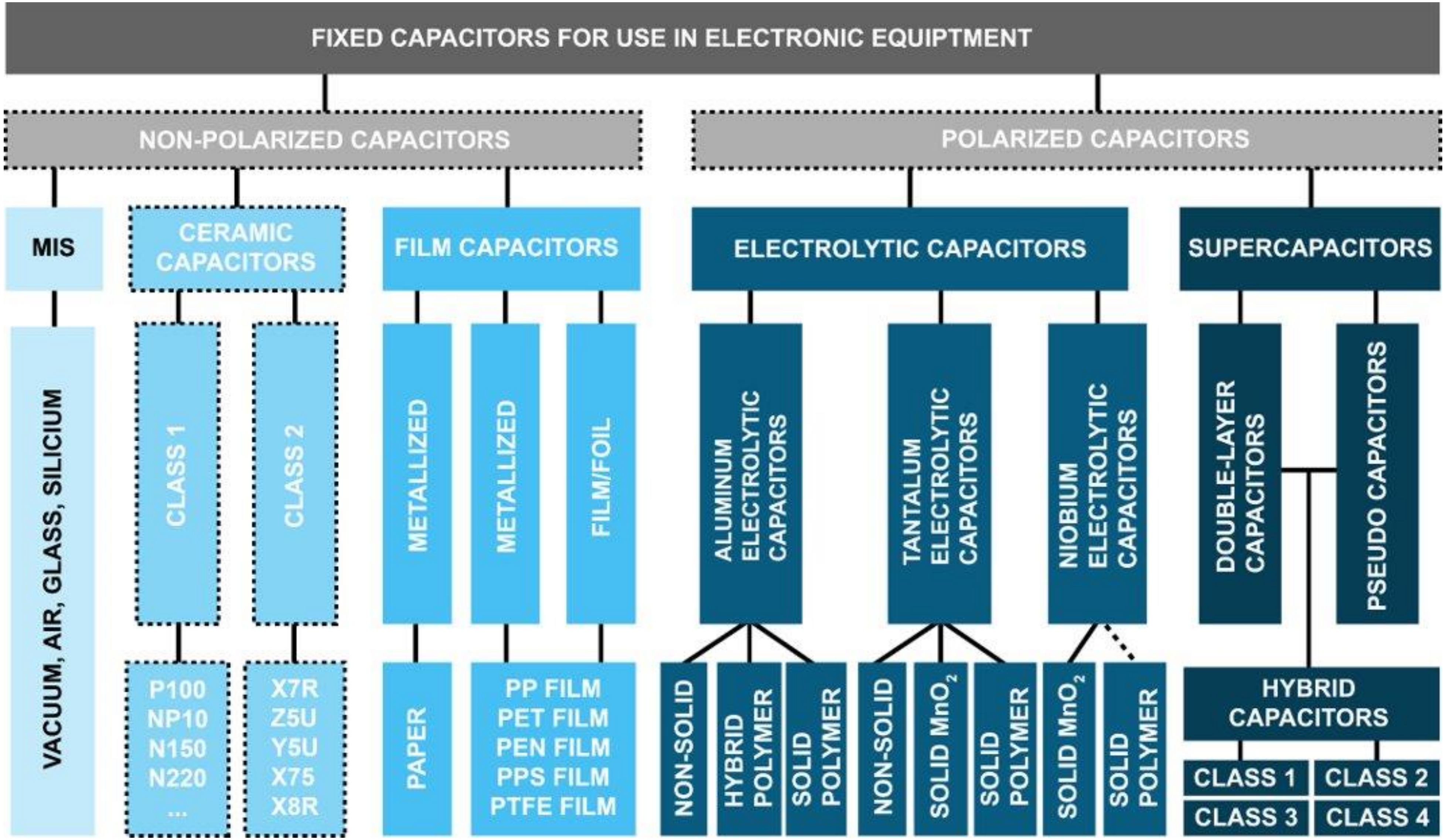
Typical User Conditions: 0.5xRV, 50°C

PRODUCT	*LOTS TESTED*	*PIECES TESTED*	*DEVICE HOURS*	*EQUIVALENT DEVICE HRS*	*FAILURE RATE (λ%)*	*FAILURE RATE (FIT)*	*MTBF HOURS*
0402 Accu-P	2272	45440	4.54E+07	2.91E+12	2.60×10^{-6}	2.60×10^{-2}	3.85×10^{10}

NOTES:

1. FAILURE RATE (λ%) IS CALCULATED IN PERCENT PER 1000 HOURS AT 95% CONFIDENCE LEVEL
2. 1 FIT = 1 FAILURE IN 10^9 HOURS AT 95% CONFIDENCE LEVEL

Recap



FIXED CAPACITORS FOR USE IN ELECTRONIC EQUIPTMENT
NON-POLARIZED CAPACITORS
POLARIZED CAPACITORS
MIS
CERAMIC CAPACITORS
FILM CAPACITORS
ELECTROLYTIC CAPACITORS
SUPERCAPACITORS
VACUUM, AIR, GLASS, SILICIUM
CLASS 1
CLASS 2
METALLIZED
METALLIZED
FILM/FOIL
ALUMINUM ELECTROLYTIC CAPACITORS
TANTALUM ELECTROLYTIC CAPACITORS
NIOBIUM ELECTROLYTIC CAPACITORS
DOUBLE-LAYER CAPACITORS
PSEUDO CAPACITORS
P100 NP10 N150 N220 ...
X7R Z5U Y5U X75 X8R
PAPER
PP FILM PET FILM PEN FILM PPS FILM PTFE FILM
NON-SOLID
HYBRID POLYMER
SOLID POLYMER
NON-SOLID
SOLID MnO_2
SOLID POLYMER
SOLID MnO_2
SOLID POLYMER
HYBRID CAPACITORS
CLASS 1
CLASS 2
CLASS 3
CLASS 4

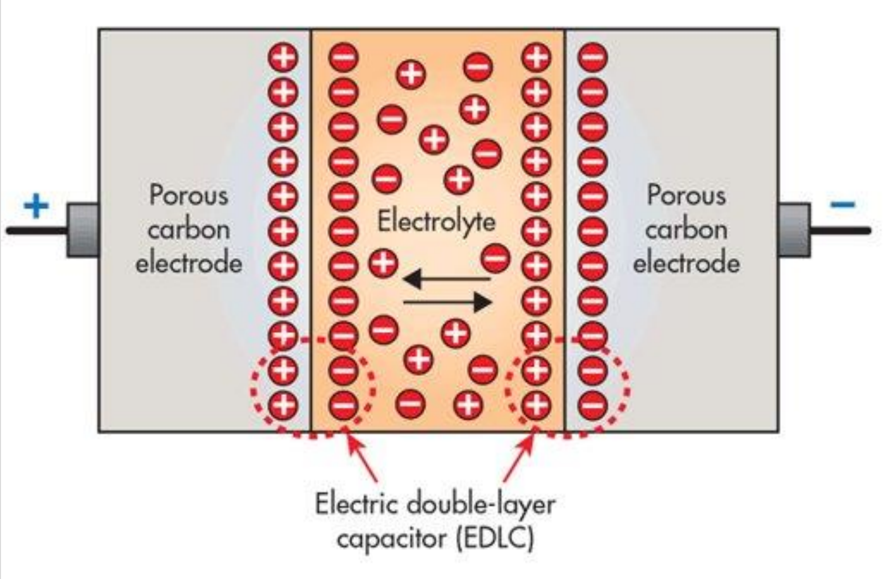
SuperCapacitors

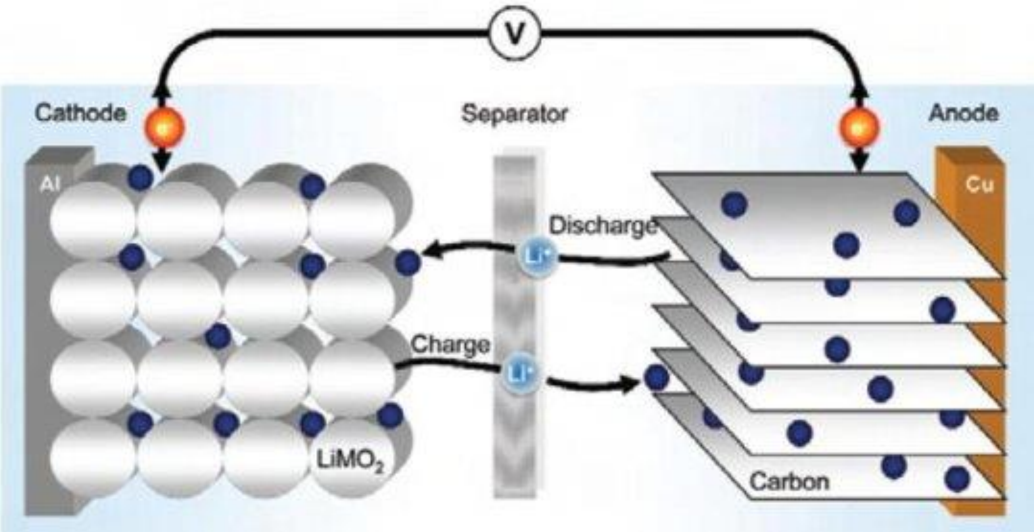
SuperCapacitors

Electrochemical Double Layer Capacitor

- High Capacitance / Low Voltage Cap
- Bridges electrolytic and rechargeable battery spectrum
- ~100x more energy per unit mass/volume of Al Electrolytic
- Fast Charge/Discharge
- Can make into modules

SuperCaps vs. Battery





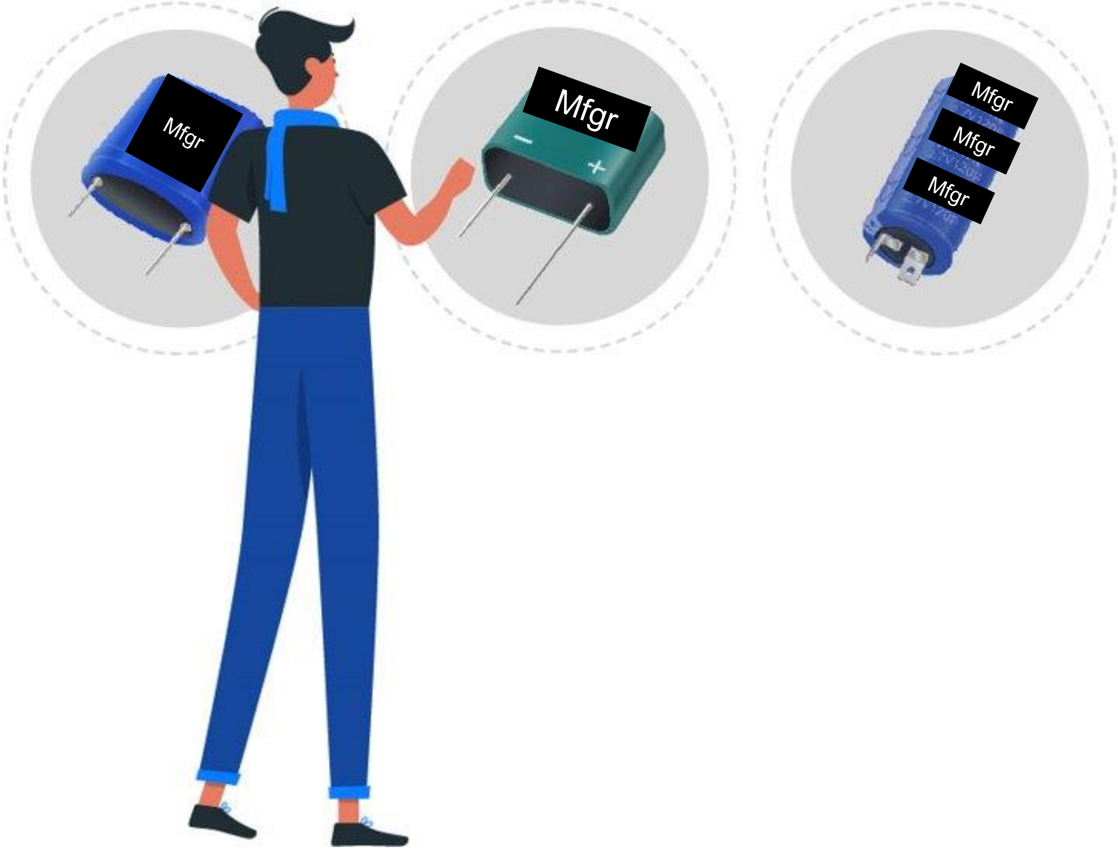
Characteristic Comparisons		
Characteristic	**SuperCap**	**Li-ion Battery**
Charge Time	1 - 10 secs	10 - 60 mins
Cycle Life	1 million	500+
Cell Voltage	2.1V - 3.3V	3.6V - 4.2V
Specific Energy	5	100 - 200
Specific Power	~10,000	1,000 - 3,000
Cost per Wh	> $10	$0.50 - $1
Service Life in Automobile	10+ years	5 - 10 years
Charge Temperature	-55°C to +90°C	0°C to +45°C
Discharge Temperature	-55°C to +90°C	-20°C to +60°C

Direct Comparisons	
SuperCaps	
Pros	**Cons**
Long life cycle	Low specific energy
High load currents	Linear discharge voltage
Fast charging times	Slightly higher self-discharge
Good temperature performance	High cost per Wh
Batteries	
Pros	**Cons**
Power density	Limited life cycle
Storage capability	Voltage and current limitations
Better leakage current	Long charging times
Constant voltage	Very temperature sensitive

Selecting Which SuperCap Technology

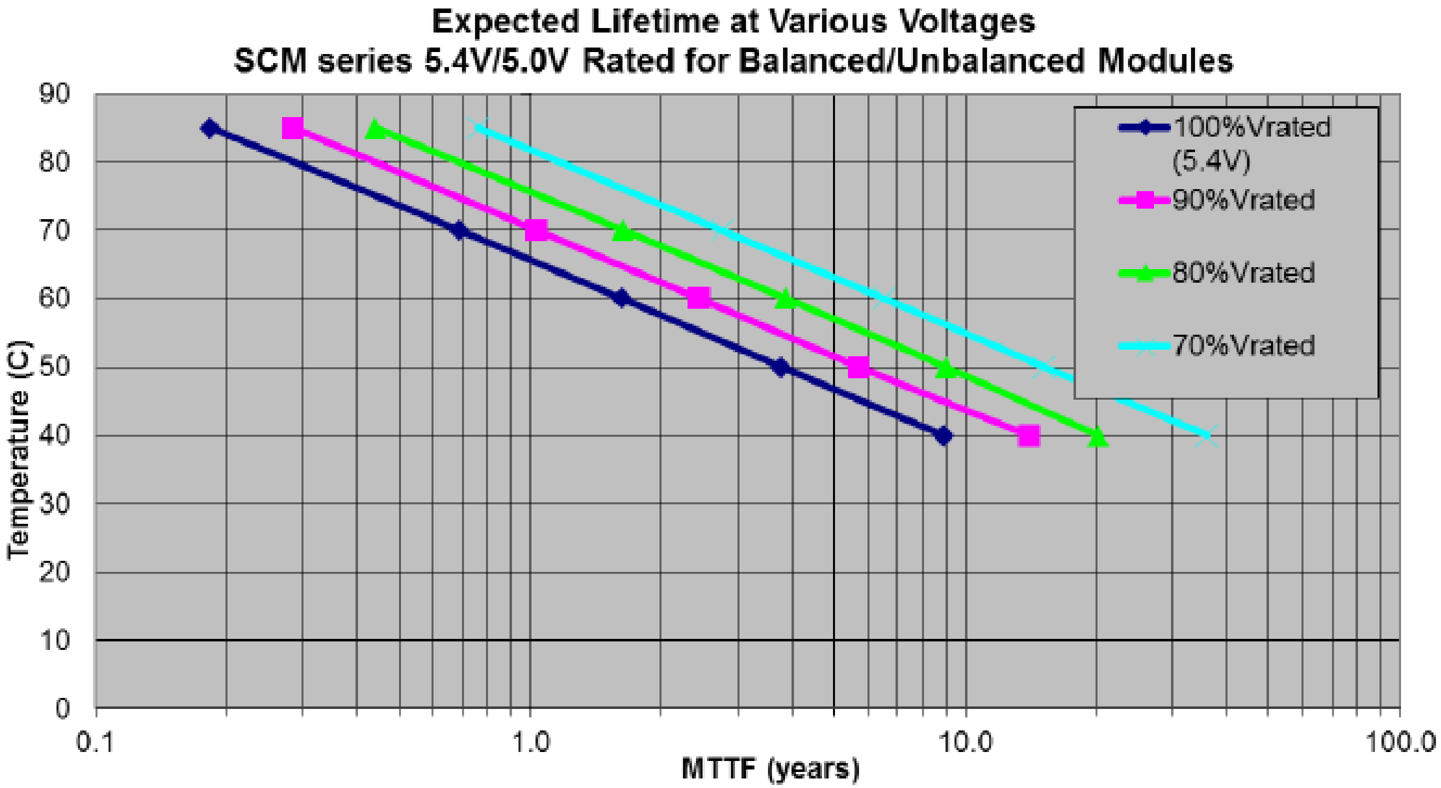
Key Things to Know Before Selection:

- Identifying the operating temperature range is most critical
- Understanding the application of either Energy Harvesting, Pulse Power, Power Hold-Up, or Battery Replacement
- Importance of Equivalent Series Resistance (ESR) and Leakage Current (LC) on the design
- Operating voltage of the application
- Expected lifetime

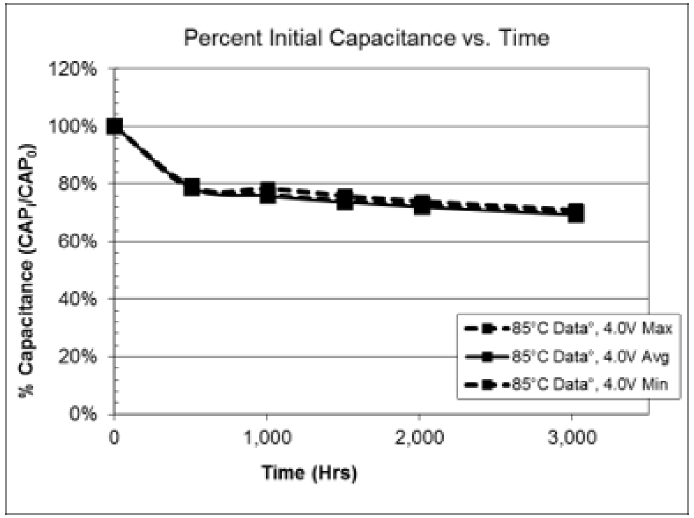


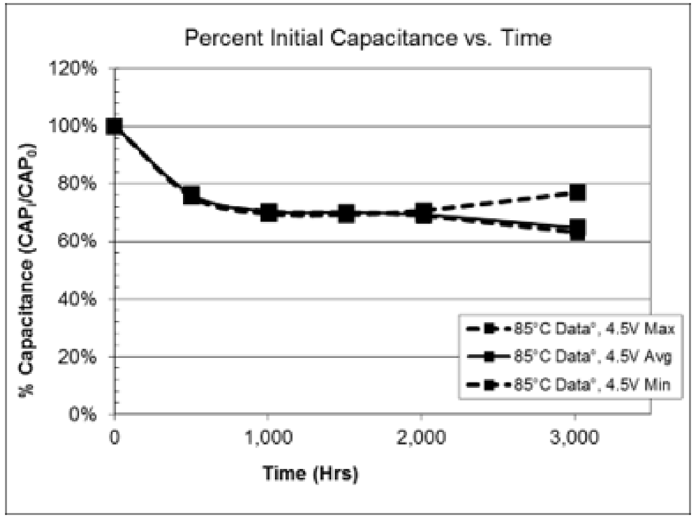
Understanding Life-Time

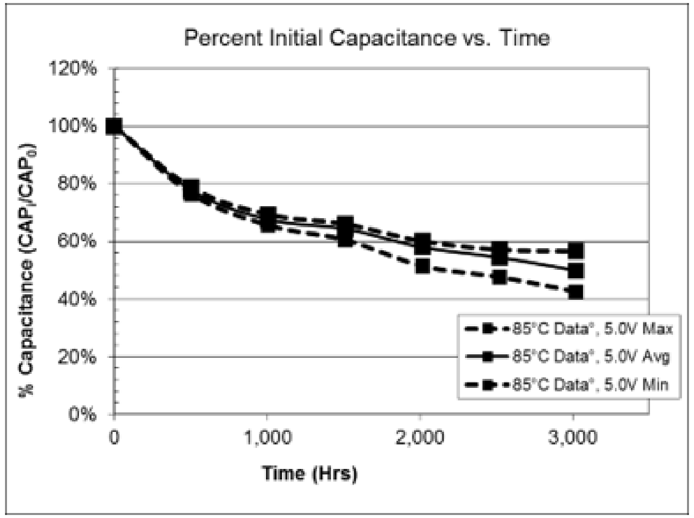
- Life-time is a function of voltage and temperature
- From internal testing and "rule of thumb," we know that life-time doubles for every 10ºC lower operating temperature, and again doubles for every 0.1V lower operating voltage.



Life-Time Test Data



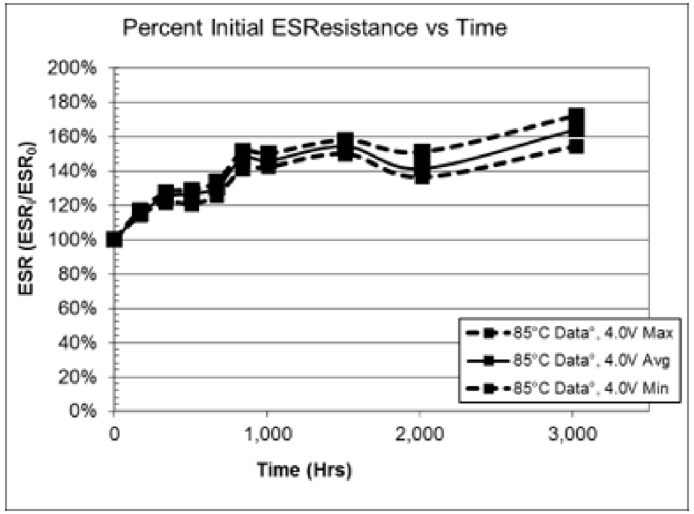


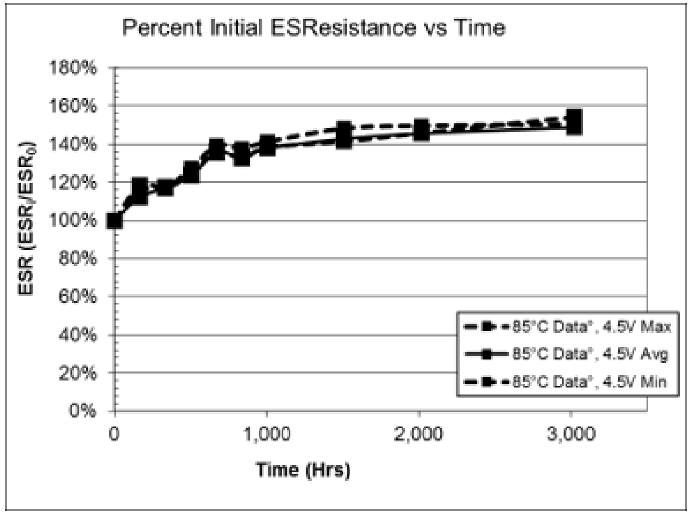


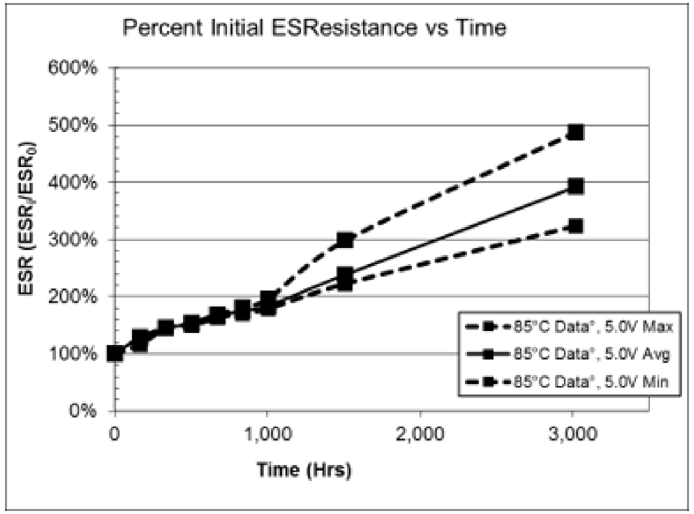
4.0V SCM at 85°C

4.5V SCM at 85°C

5.0V SCM at 85°C



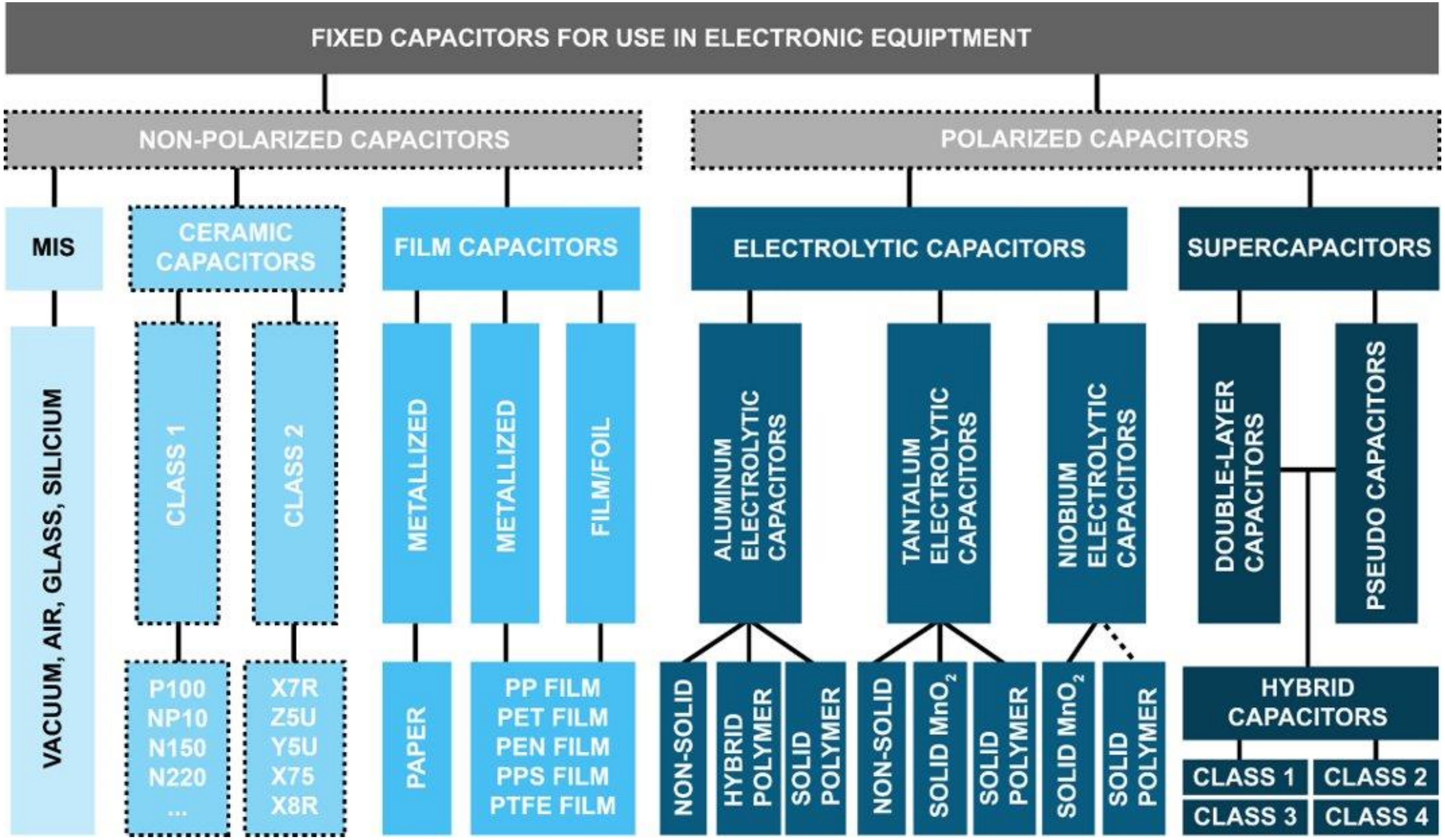




Custom SuperCap Modules

Modules of 48V 165F & 16V 500F are common today due to active balancing IC chipsets for series parallel capacitor connection. Larger modules easily possible.

Summary


FIXED CAPACITORS FOR USE IN ELECTRONIC EQUIPTMENT
NON-POLARIZED CAPACITORS
POLARIZED CAPACITORS
MIS
CERAMIC CAPACITORS
FILM CAPACITORS
ELECTROLYTIC CAPACITORS
SUPERCAPACITORS
VACUUM, AIR, GLASS, SILICIUM
CLASS 1
CLASS 2
METALLIZED
METALLIZED
FILM/FOIL
ALUMINUM ELECTROLYTIC CAPACITORS
TANTALUM ELECTROLYTIC CAPACITORS
NIOBIUM ELECTROLYTIC CAPACITORS
DOUBLE-LAYER CAPACITORS
PSEUDO CAPACITORS
P100
NP10
N150
N220
...
X7R
Z5U
Y5U
X75
X8R
PAPER
PP FILM
PET FILM
PEN FILM
PPS FILM
PTFE FILM
NON-SOLID
HYBRID POLYMER
SOLID POLYMER
NON-SOLID
SOLID MnO_2
SOLID POLYMER
SOLID MnO_2
SOLID POLYMER
HYBRID CAPACITORS
CLASS 1
CLASS 2
CLASS 3
CLASS 4