ITW Paktron

Polymer Film Capacitors

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This presentation covers current topics in polymer film capacitors commonly used in power systems. Polymer film capacitors are essential components in higher voltage and higher current circuits. Unlike most other dielectric systems, film capacitors feature low loss factor at very low temperature. Long life and graceful aging are properties of film capacitors.

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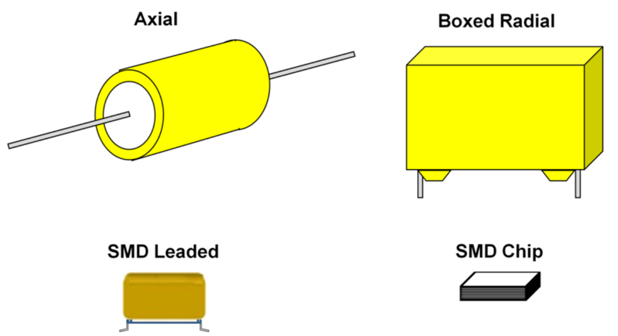
Examples of Commercial Packaging Styles

Polymer Film Capacitors



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Polymer or plastic film capacitors cover a very wide range of size, voltage and capacitance variations. Film capacitors are valued for their stability under higher voltage loads and high ripple current. This is a depiction of axial and radial leaded DC film capacitors in wire leaded and SMT configurations. The smaller PET film capacitors compete directly with ceramic capacitor types.

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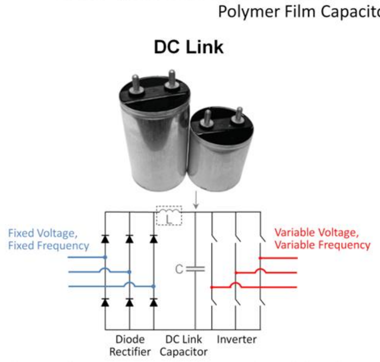
Examples of Power Capacitor Packaging Styles

Polymer Film Capacitors



The DC Link capacitor smoothes the DC voltage, linking the rectifier to a switching DC-DC converter or DC to AC inverter.

AC Motor Run

IGBT Snubber

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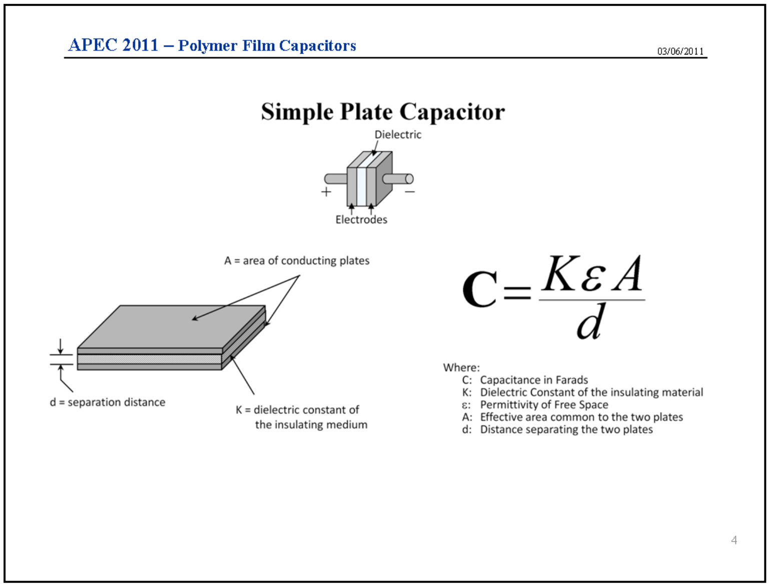
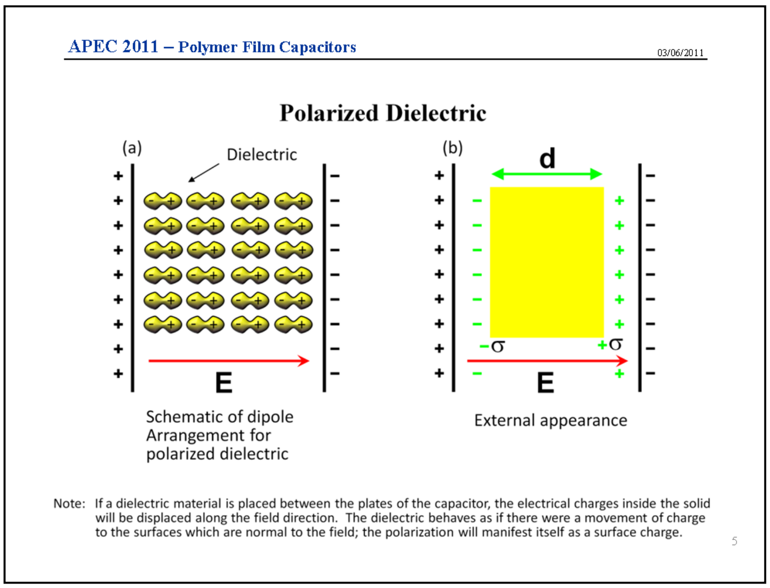
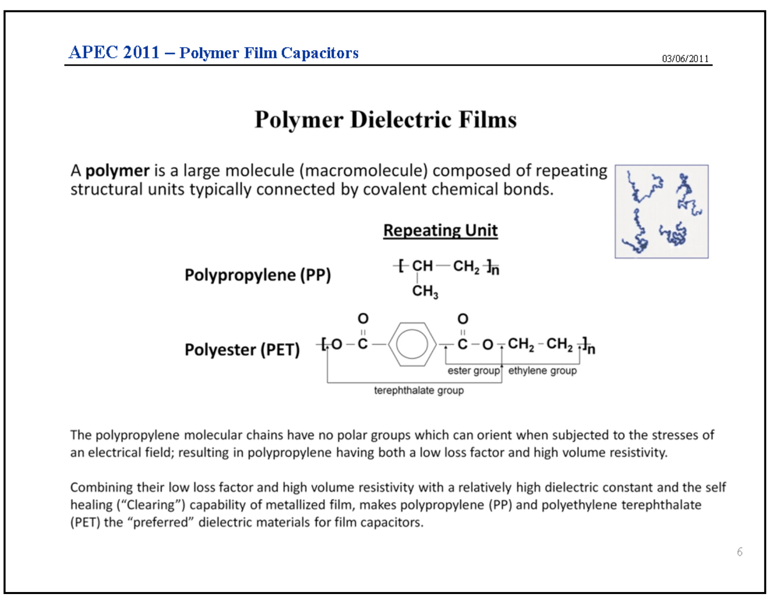
AC rated film capacitors are mainly based upon polypropylene dielectric that has very low loss factor and can handle high current at lower frequencies. These capacitors have lower capacitance value than aluminum electrolytic types, but they are capable of handling much higher current per unit volume. PP film capacitors offer both performance and system cost advantages over 450 volts compared to electrolytic types. Usage in boost converters, DC link decoupling and inverter feeds are rapidly growing applications.



Note that a reduction of ½ the dielectric thickness (d) will provide a capacitance of 4 times in the same volume. Film capacitor producers have concentrated on reducing the dielectric thickness in order to increase the capacitance per unit volume. The range of dielectric constant (K) is only between 2 and 3.3 that of a vacuum. This relatively low dielectric constant motivates the manufacturer to provide a large surface area of electrode. Generally low K materials are very stable under voltage, temperature and current loads.



This is the internal arrangement that takes place within the semi-polarizing film PET.



PP is a small and simple molecule. PET is 'heavier" but also provides a stronger and higher tensile strength film that con be bi-axially oriented into very thin films.

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Polymer Film Dielectrics

Type	Class
Polyethylene terephthalate – PET (polyester)	Production
Polypropylene – PP	Production
Polyphenylene sulfide – PPS	Limited Use
Polyethylene naphthalate – PEN	Limited Use
Polycarbonate – PC	Limited Use
Polystyrene – PS	Specialty
Polysulfone	Specialty
Poly(4,4'-oxydiphenylene-pyromellitimide) – K (Kapton)	Specialty
Polytetrafluoroethylene – PTFE (Teflon)	Specialty
Polyvinyl fluoride – PVF2	Specialty
Polyvinylidene Fluoride – PVDF	Specialty
Fluorene Polyester – FPE	Specialty

Note: Materials such as PEN, PPS and PC are commercially available, but are single source products.

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PET and PP totally dominate the film dielectric market. Development work is continuing with PEN and PPS materials. Higher temperature films command a premium but are either single sourced or have poor availability as of this writing.

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Dielectric Comparison Summary

	PET	PP	PEN	PPS
DC Life				
Capacitance Change	< 5.0%	< 3.0%	< 5.0%	< 5.0%
DF (Tan δ) @ 1KHz	< 1.0%	< 0.1%	< 0.8%	< 0.2%
Insulation Resistance	> 50% initial	> 50% initial	> 50% initial	> 50% initial
Moisture				
Capacitance Change	< 7.0%	< 5.0%	< 7.0%	< 7.0%
DF (Tan δ) @ 1KHz	< 1.0%	< 0.2%	< 0.8%	< 0.2%
Insulation Resistance	> 50% initial	> 50% initial	> 50% initial	> 50% initial
Stability (1 year storage)				
Capacitance Change	< 2.0%	< 0.5%	< 2.0%	< 1.0%

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Film capacitors are known for their inherent stability and long life—usually 10 to 20 years.

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Typical Dielectric Strengths

Material Type	Dielectric Strength (kv/mm)
Air	3
Barium titanate	2-10
Glass	15
Mica	63
Paper	14
Polycarbonate (PC)	60
Polyester (PET)	200
Polyphenylenesulfide (PPS)	200
Polypropylene (PP)	300
Polystyrene (PS)	100
Polyvinylidenefluoride (PVDF)	210
Teflon (PTFE)	60

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Most polymers offer very high dielectric strength. The highest is that of polypropylene. As a result, most high voltage devices use PP due to its high DS and relatively low cost for use in large units.

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Film Dielectrics Dissipation Factor

Inherent % Dissipation Factor vs. Frequency					
Freq. (Hz)	PET	PEN	PPS	PC	PP
100	0.250	0.100	0.050	0.065	0.020
1,000	0.400	0.200	0.060	0.080	0.020
10,000	0.950	0.450	0.080	0.100	0.020
100,000	1.550	0.600	0.100	0.160	0.020
1,000,000	1.700	0.900	0.180	0.800	0.030

New film dielectrics are being made available to improve high
Frequency response and increase thermal withstanding.

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Polypropylene has excellent AC loss factor at low frequency. PET has good characteristics given its 99.75% efficiency at 100 hertz. Dissipation factor relates to the amount of energy dissipated as heat through every AC cycle.

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Film Dielectric Thickness

	Polyester			Polypropylene			Polystyrene			Polycarbonate		
	Gauge	Inches	Microns	Gauge	Inches	Microns	Gauge	Inches	Microns	Gauge	Inches	Microns
UTF	3.6	0.000036	0.9									
UTF	4.0	0.000040	1.0									
UTF	4.8	0.000048	1.2									
UTF	5.6	0.000056	1.4									
UTF	6.0	0.000060	1.5							6.0	0.000060	1.5
UTF	7.0	0.000070	1.8									
UTF	8.0	0.000080	2.0							8.0	0.000080	2.0
UTF	10	0.000100	2.5									
				11	.000110	2.75						
	12	0.000120	3.0	12	.000120	3.0						
	14	0.000140	3.5	14	.000140	3.5				14	0.000140	3.5
	16	0.000160	4.0	16	0.000160	4.0						
	19.2	0.000192	4.8									
	20	0.000200	5.0	20	0.000200	5.0						
	24	0.000240	6.0	24	0.000240	6.0				24	0.000240	6.0
	32	0.000320	8.0	32	0.000320	8.0	32	0.000320	8.0			
	40	0.000400	10.0	40	0.000400	10.0	40	0.000400	10.0	40	0.000400	10.0
	48	0.000480	12.0	48	0.000480	12.0				48	0.000480	12.0
	60	0.000600	14.0	60	0.000600	14.0	60	0.000600	14.0			
	75	0.000750	19.0	75	0.000750	19.0	75	0.000750	19.0			
	100	0.001000	25.0				100	0.001000	25.0			

UTF – Ultra Thin Film

Note: Polyester (PET) film dominates the ultra-thin film arena.
Thinner polypropylene (PP) films are a priority development.

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PET has the distinct advantage of availability in "ultra thin" dimensions. PET has much greater tensile strength than PP. PET also has a >50% higher dielectric constant. This combination allows a much smaller package in PET versus PP. PET styles are common from 50 to over 500 volts.

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Film Dielectric Comparison

Characteristics Comparison		PET	PP	PEN	PC
Capacitance	Range (µF)	0.001 – 50.0µF	0.001 – 1600.0µF	0.001 – 50.0µF	0.001 – 50.0µF
	Tolerance – Min	± 5.0%	±0.5%	± 5.0%	± 1.0%
	Tolerance – Std	± 10.0%	± 5.0%	± 10.0%	± 10.0%
Dissipation Factor	% @ 1KHz	1.0%	0.1%	0.8%	0.3%
Insulation Resistance	≤ 1.0 µF	1.0 x 10^{9} Ωs	3.0 x 10^{11} Ωs	1.0 x 10^{9} Ωs	2.0 x 10^{11} Ωs
	> 1.0 µF	1,000 MΩ x µF	5.0 x 10^{10} Ω x µF	1,000 MΩ x µF	5.0 x 10^{10} Ω x µF
Voltage Range	VDC	25 – 60,000	100 – 1,000	25 – 1,000	100 – 1,000
Dielectric Absorption	%	0.5%	0.05%	0.8%	0.35%
Dielectric Constant		3.25	1.8	3.16	2.2
Glass Transition	°C	80°C	-10°C	122°C	148°C
Operating Temperature	Range °C	-55 to +125°C	-55 to +85°C	-55 to +125°C	-55 to +125°C
Melting Point	°C	255°C	170°C	269°C	267°C
Max SMD Soldering Temp.	°C	220°C - 245°C	N.A.	250°C	220°C

Note: PET and PEN are used in input circuits.
PP is widely used in AC and high current applications.

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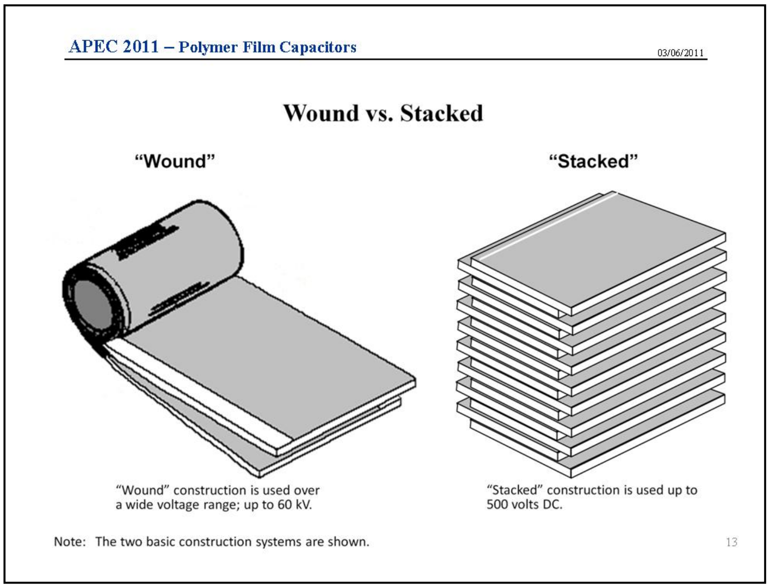
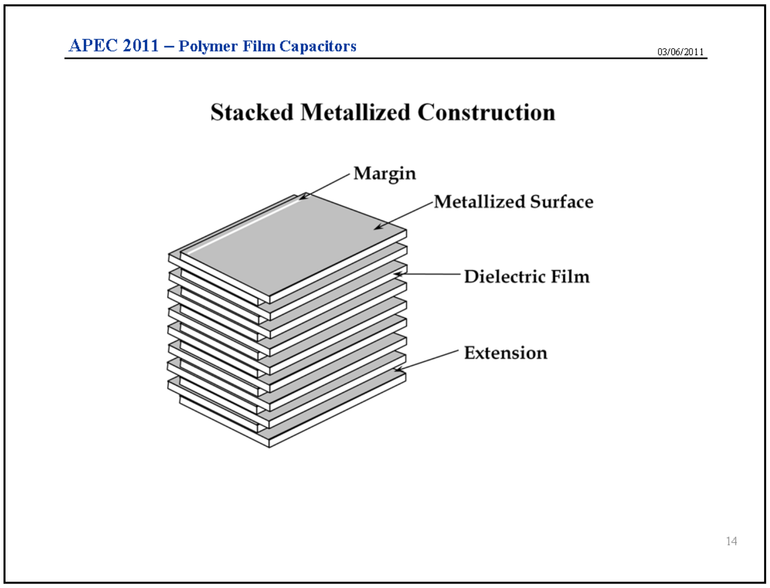
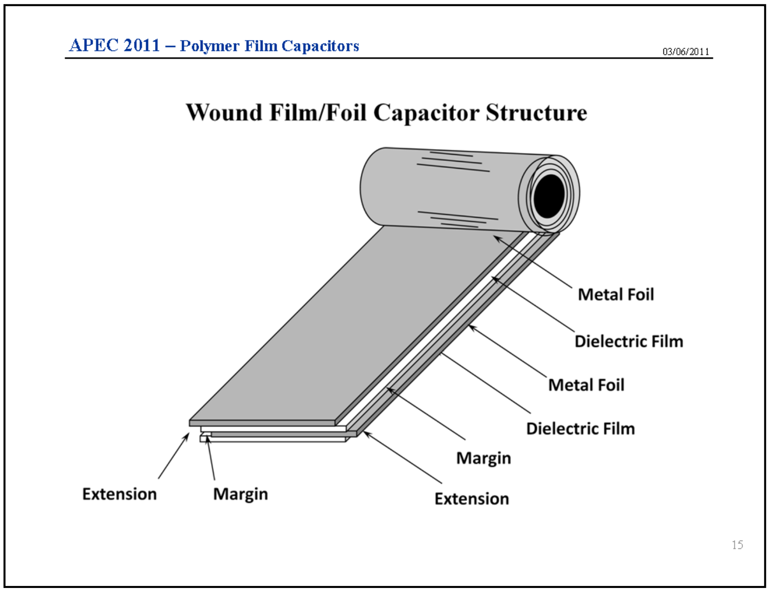
An advantage of PET versus PP is higher operating temperature and much higher actual melting point. This allows surface mount compatible PET devices while PP is not suitable for high temperature surface mount.



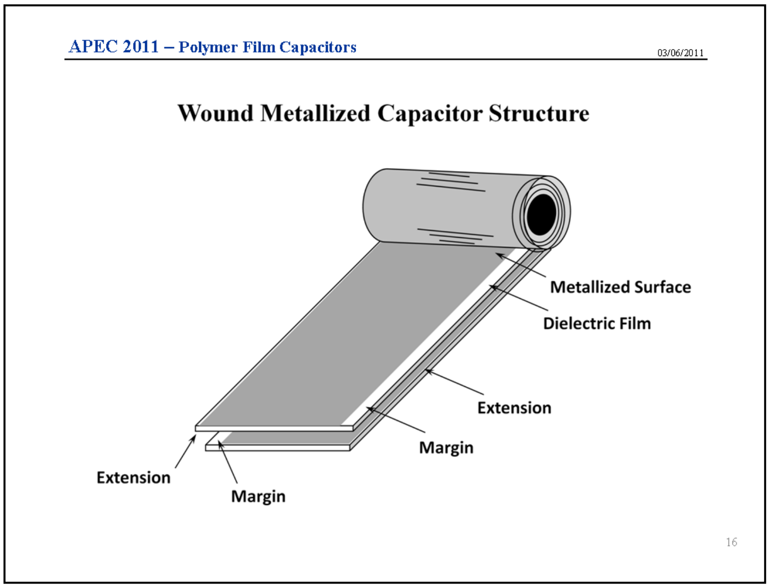
Most film capacitors fall under the classification of wound or stacked construction. Each has its advantages and disadvantages. Stacked or "multilayer" capacitors are more size efficient and have much better electrical characteristics at high frequency. Wound capacitors can reach much higher voltage ratings due to their wide and continuous safety margins. The severed or "cut" edge of stacked capacitors limits their DC voltage rating.



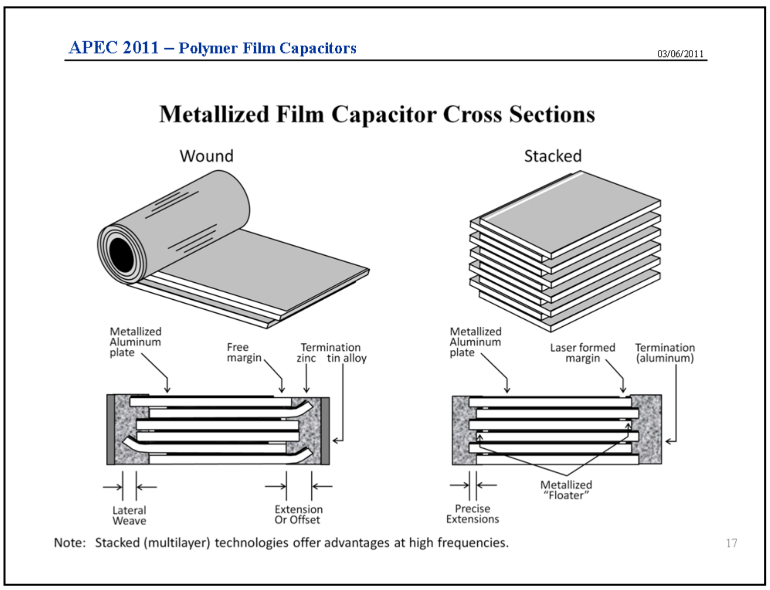
Multilayer film systems minimize the size of the safety margins and lateral extensions providing higher capacitance per unit volume. They offer much higher pulse ratings than most wound capacitors.



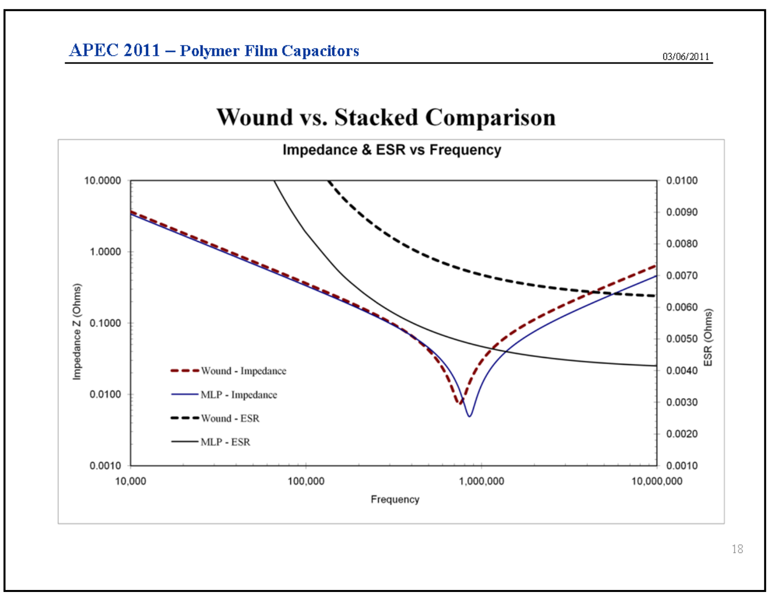
This is a typical plain film and extended foil electrode construction. This construction is used in special high current applications. A disadvantage is a short circuit failure mode inherent in thick foil devices.



Metallized film capacitors utilize a deposited metal (aluminum or zinc) that is only a few hundred angstroms thick. This compares to a thin foil electrode of typically ranging in thickness from 0.20 to 1.0 mil. The metallization is so thin it allows for "clearing" and avoidance of short circuit failure mode.



The stacked film or multilayer film construction was actually an improvement over the older wound film technology. It provided much improved film extensions and the ability to make better contact to every layer with the termination metal. Faults in the contact of the termination to the layers are a major cause for concern. The use of aluminum on aluminum construction provides a better high frequency capacitor with lower ESR. The use of similar metal in the electrode and termination improves the moisture resistance of the part.



This comparison shows the better high frequency response of the stacked or multilayer capacitor. It is also 40% smaller in volume.

Wound vs. Stacked

Parameter	Worst Case Sample Readings	
	Stacked	Wound
ESR @ 500KHz	5.29mΩ	7.74mΩ
Resonance Freq.	853KHz	743KHz
Eqv. L	3.1nH	6.9nH
Eqv. R	4.86mΩ	7.35mΩ

Typical readings taken on 4.7mfd 100vdc units.

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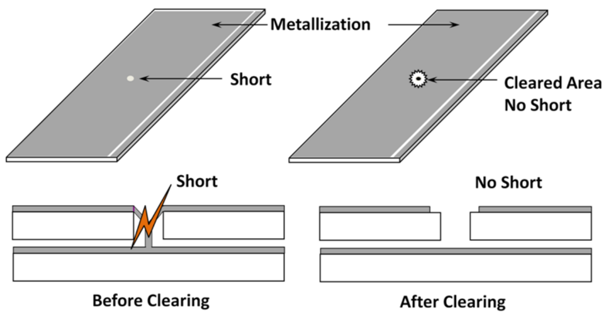
The equivalent series inductance is better for the stacked unit. The ripple current rating is higher. The resonant frequency shown includes a contribution of the bridge fixture, but the comparison is valid.

Metallized Polymer Film Clearing



"Clearing" is the removal of a flaw, such as a thin spot, or metal particle in the dielectric of a metallized capacitor by using the energy stored in the capacitor to vaporize the very thin metallized material in the immediate vicinity of the flaw. This process is often referred to as "self-healing" and helps to greatly extend the life of MLP capacitors.

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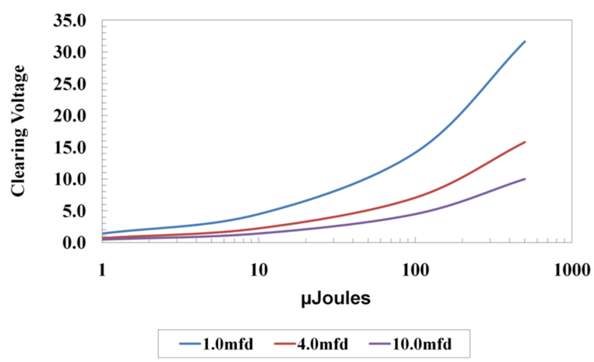
Metallized film capacitors are voltage "cleared" during the production process. Under specified usage they should not clear again. However, during a high voltage event, the film has the ability to self clear. This is a strong advantage over film/foil types. It is also a very strong advantage over ceramic capacitors that are essentially thick electrode devices that can and do fail short.

Clearing Voltage vs. Joules



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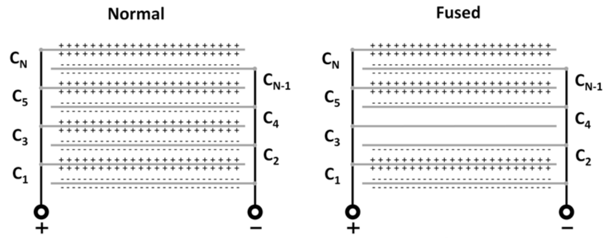
This is a typical curve that describes the energy required to clear a fault. Faults in the film are cleared after the film is metallized and at least once during the capacitor construction.

Capacitor Fusing



$$C_t = C_1 + C_2 + C_3 + C_4 + C_5 \ldots + C_N$$

$$C_t = C_1 + C_2 + C_3 + C_4 + C_5 \ldots + C_N$$

Another advantage in the stacked film technology is its ability to protect both itself and the circuit that it is in via self fusing when subjected to over voltage / over current conditions. Due to the stacking methodology of its construction, each capacitor is actually composed of hundreds of identical, small valued capacitors, all tied in parallel. Should an extreme case over voltage / over current condition occur, the capacitor will fuse at the weakest capacitor link and disconnect that sub-capacitor from the capacitor proper. While this will result in a loss in total capacitance, losing 2 stacks (sub-capacitors) out of 1000 would result in a loss of only 0.2%

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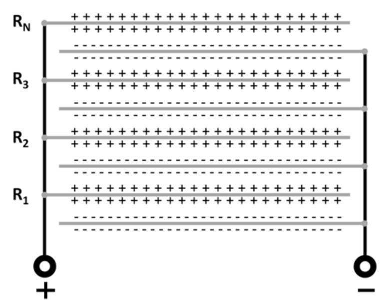
An interesting feature of stacked film capacitors is the ability to self fuse during a high voltage or high power event. Wound capacitors do not have this feature and the loss factor can rise due to termination failure. The stacked film units can partially fuse, losing a few layers and not increase parasitic ESR of the whole stack.

Electrode Resistance



$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_N}$$

Note: Polymer capacitors can reach over 6,000 layers with each layer contributing to a reduction in the total Equivalent Series Resistance (ESR).

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Film capacitors depend upon thousands of stacked layers to reach the desired capacitance (and related current rating). These parallel layers also lower the series resistance of the package. Today film capacitors offer lower ESR than ceramic X7R type over the whole frequency range.

Film Capacitor Technology Advances

- Segmented Electrodes on Polypropylene Films
- Special Coatings on Polymer Films
- Thin Films Under One (1) Micrometer Thickness
- Polymer Films Conditioned for Reflow Solder Temperatures

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Film capacitor manufactures work with producers of the thin film and with vacuum metallization converters to enhance the properties of the parts. Main objectives are to reduce the size, increase the operating voltage and extend the useful life of the product.

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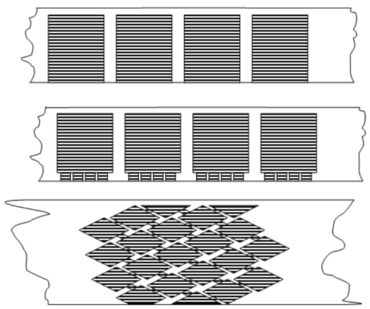
Typical Segmented Patterns on Metallized Film



Note: Segmenting films either in a 'T' or 'X" configuration offers a safe 'fusing' in high voltage applications. These types of patterns are used primarily on PP films.

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One of the most significant advances in polypropylene capacitors is the use of segmented film. Specifically designed metal electrode patterns are masked onto the film creating thin conductive links that can act like a fuse under high voltage loads. This advance has allowed the PP devices to be used at higher voltage per micron polymer thickness while avoiding the increase in loss factor due to termination disconnect from the primary electrode. This method is commonly used in the widely used PP "X Capacitors" used in input filter networks.

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Polyester Film vs. Ceramic Capacitor Comparison

Characteristics Comparison		PET	X7R
Capacitance	Range (µF) Tolerance – Min Tolerance – Std	0.001 – 50.0µF ± 5.0% ± 10.0%	0.001 – 22.0µF ± 5.0% ± 10.0%
Dissipation Factor	% @ 1kHz	1.0%	3.0%
Insulation Resistance	≤ 1.0 µF > 1.0 µF	1.0 x 10^9 Ωs 1,000 MΩ x µF	1.0 x 10^9 Ωs 1,000 MΩ x µF
Voltage Range	VDC	25 – 50,000	50 – 500
Dielectric Absorption	%	0.5%	2.5%
Dielectric Constant		3.25	700…2000
Density	g / cm^3	1.39	5.85
Operating Temperature	Range °C	-55 to +125°C	-55 to +125°C
Melting Point	°C	255°C	N.A.
Temperature Coefficient	% Δ Cap	± 5.0%	± 15.0%
Voltage Coefficient	% Δ Cap @ 100vdc	N.A.	-35.0%
Capacitance Aging	% / decade hour	N.A.	-2.0%
Piezoelectric		No	Yes
Prone to cracking		No	Yes
Self-clearing (self-healing)		Yes	No
Failure Mode	Typical	Open	Short
Reliability		High	Moderate

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PET capacitors compete directly with X7R ceramic capacitors based upon their superior loss factor and stability under voltage. The film capacitors are generally larger than X7R types but their stability at high voltage and in cold environments mandates their use in certain applications. Note the dissipation factor advantage of the film (0.5% versus 2.5%) over the X7R ceramic translates directly into better ESR and current handling capability.

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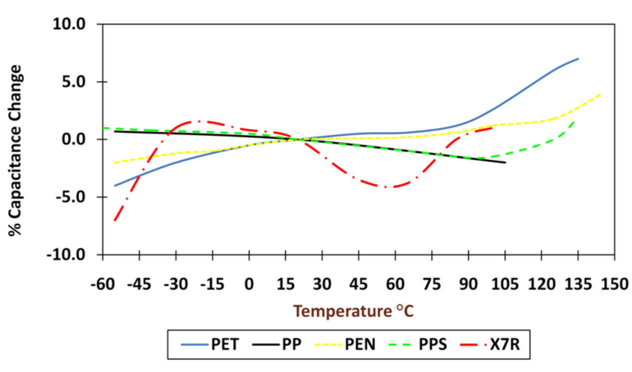
% Cap Change vs. Temperature



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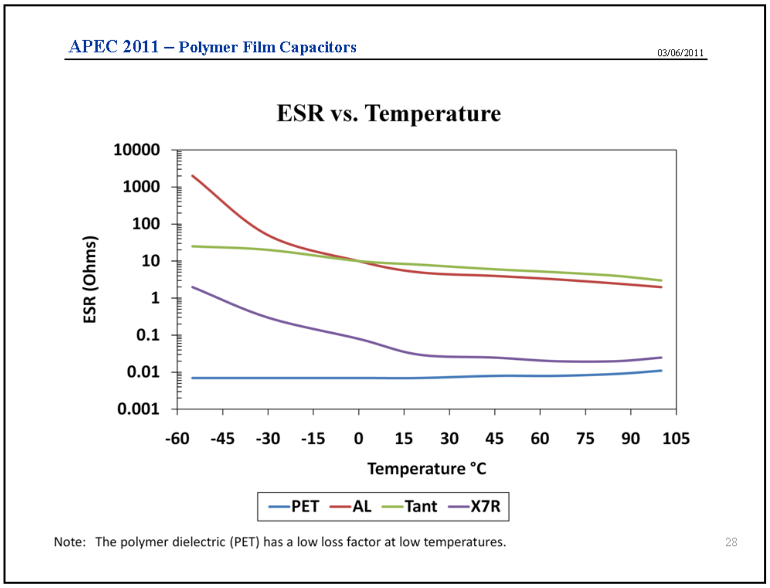
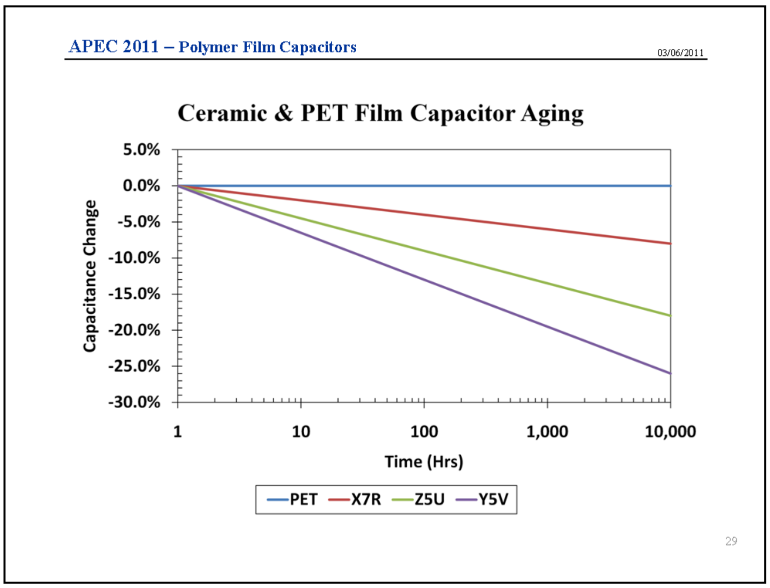
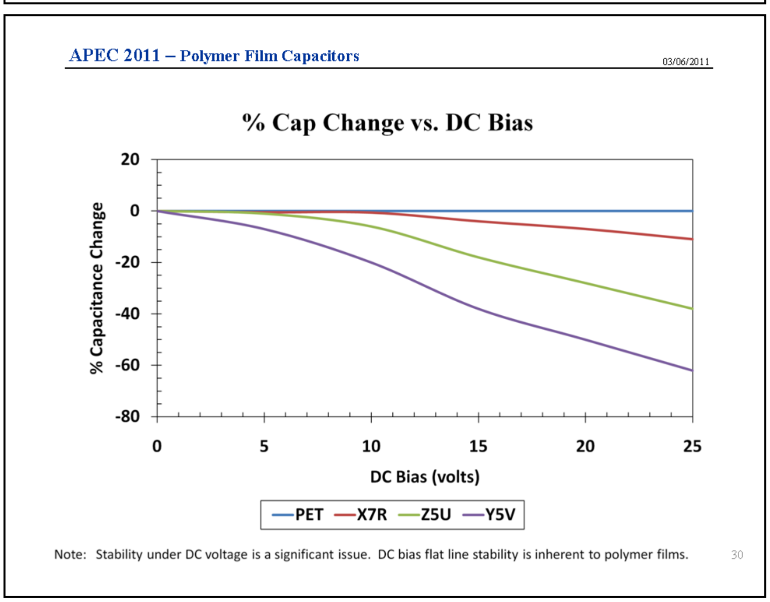
The temperature coefficient is shown for several dielectrics.



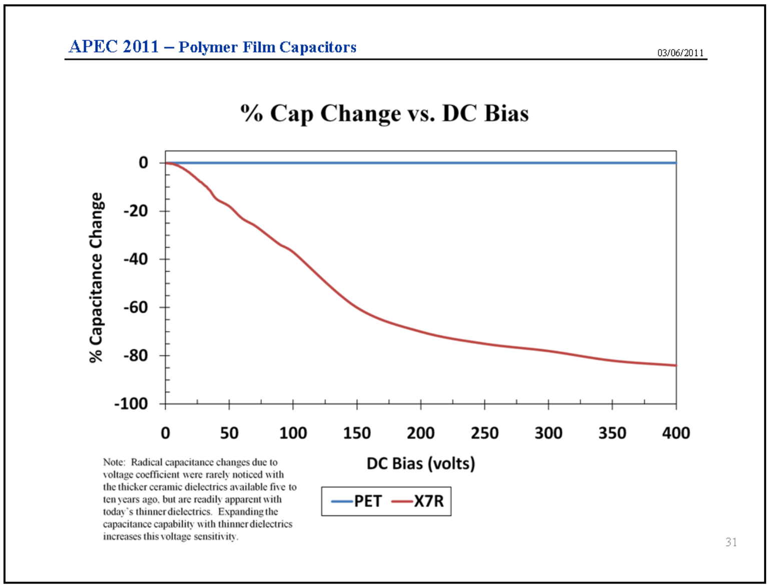
Polymer film capacitors are very stable at low temperature. This remarkable feature is very important for application at high elevation, in cold climates and naturally for avionics and aerospace.



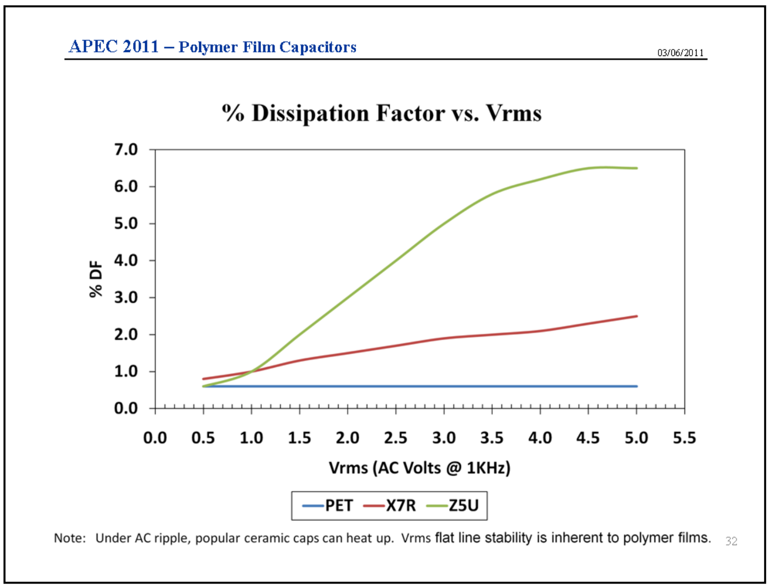
Ceramic capacitors have a built in aging factor that reduces the capacitance per decade hour of time. This occurs whether the units are powered up or not. Polymer films do not have an aging factor of this type.



Ceramic X7R capacitors drop in capacitance value proportional to the bias voltage applied. Polymer film types, however constructed, are stable under DC bias. Some engineers argue this cap drop is manageable below 10 volts.

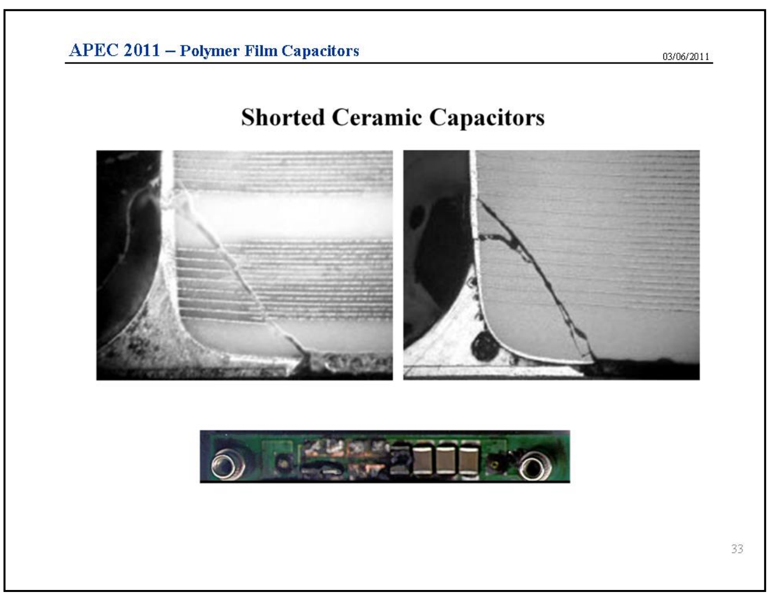


Ceramic X7R capacitors can lose a huge amount of effective capacitance value at 400 volts in this case. Film capacitors are widely used in high voltage rectified bus because of the stability under DC load, and a higher effective cap value. Unlike 10 volt applications this is clearly the realm of film caps.



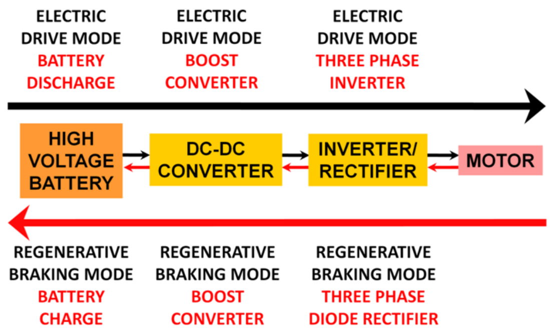
This information is not widely known or recognized by power system designers. Under AC conditions including ripple, popular ceramic capacitors worsen under load. The dissipation factor of popular ceramic capacitors increases under imposed AC. This increases the ESR and leads to increase heating of the devices.

Film capacitors, however constructed, are not affected by AC loads or ripple. Ignoring sizes differences, the impedance of the films is far superior to ceramic capacitors.



The subject of ceramic cracking along the solder fillet is a widely known issue. Ceramic chips can crack, short and explode on a 48 volt telecom bus.

Power Electronics in Hybrid Vehicles



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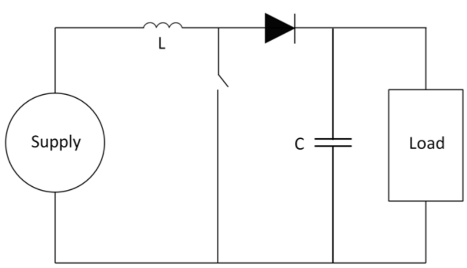
A significant and growing application for large and high voltage polypropylene capacitors exists in the hybrid vehicle (HEV) market. The boost converter uses an input filter bank around 1000 microfarads at around 600 volts. The output bank that feeds the inverter is around 3000 microfarads at similar high voltage. Since the system is bidirectional, polarized aluminum electrolytic types are not suitable. Development work on improved polypropylene and the use of thin metallization and segmented electrodes allow the use of 3.2 micron PP in 600 to 700 volt filter banks and IGBT snubbers in the system.

Boost Converter in "HEV"



Note: Good application for PP with segmented film due to the high voltages (500 – 600 V range).

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The large bidirectional polypropylene capacitor banks have been used for almost ten years with good reliability.

CE

RoHS

1. RoHS – Restriction of Hazardous Substances Directive
2. RoHS originated in Europe and is rapidly spreading worldwide.
3. RoHS is the EU's approach to "greening" the environment by banning the use of specific materials, that are considered potentially hazardous, in select electrical/electronic equipment.
4. These substances are the RoHS-6: Lead (Pb), Mercury (Hg), Cadium (Cd), Hexavalent chromium (Cr6+), Polybrominated biphenyls (PBB) and Polybrominated diphenyl ether (PBDE).
5. RoHS does not mandate the use of high temperature solder. RoHS bans lead (Pb) and its most common replacement is Pb-Free solder alloys which require much higher reflow temperatures and cycle times than tin/lead (Sn/Pb) solder.
6. The changes caused by RoHS have effectively curtailed broad market use of polymer film capacitors for convection reflow assembly because the thermal withstanding capability of common dielectric film polymers is insufficient for high temperature reflow soldering.
7. Paktron has now developed its' patent pending –FS series of shielded capacitors to address the high temperature, Pb-Free assembly market.

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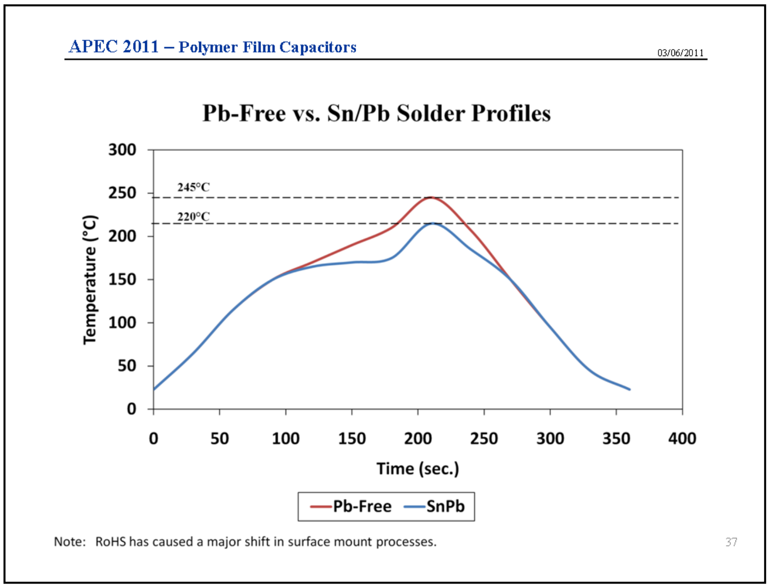
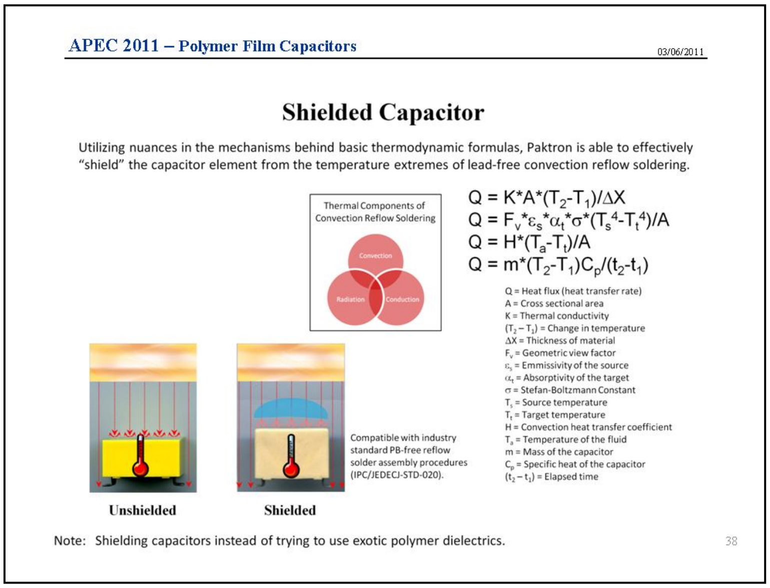
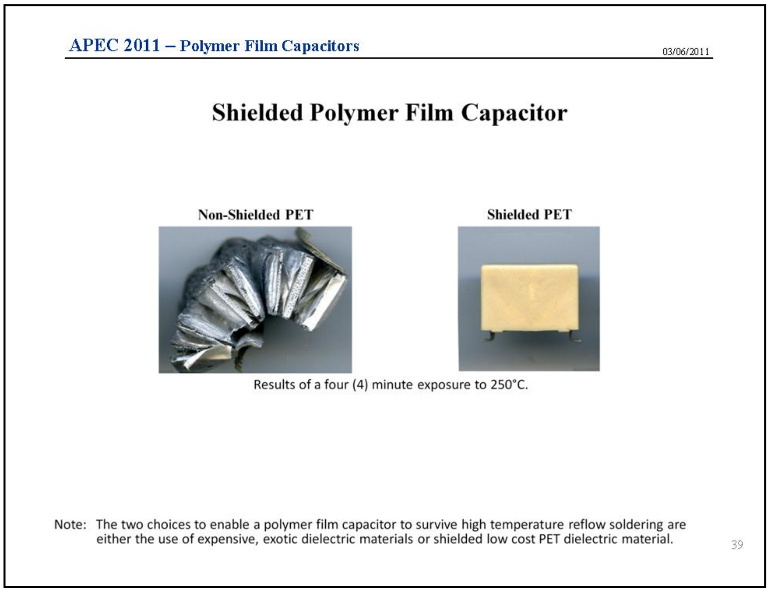
The move to lead free soldering took hold in mid 2006 with the European time line for legislation of this mandate. China has followed since.



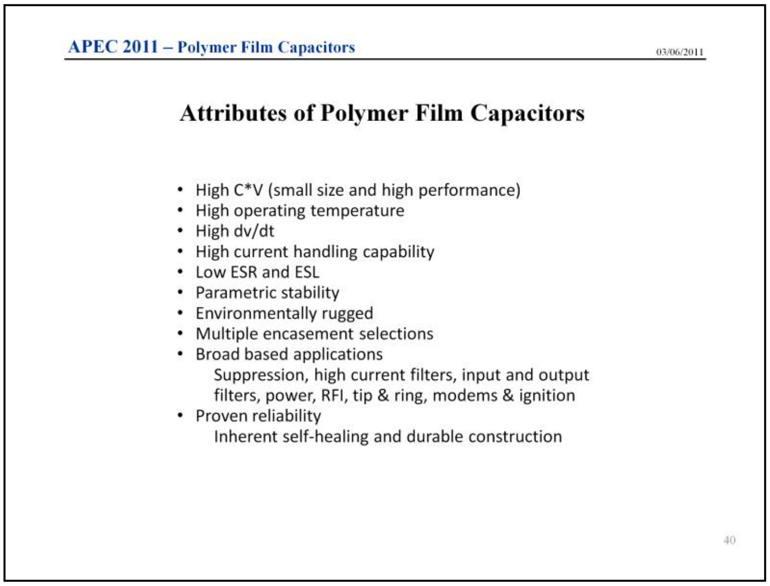
Lead-free assemblies are reflow soldered usually in convection chambers at much higher temperatures than before. SMT capacitors have to adapt to the time duration above 215°C and the peak temperature that has been studied anywhere from 245°C to 260°C. Many profiles operate the input air at 280°c and even 290°C. The oven profile shown above is a mole temperature at the surface of the circuit board.



Film capacitor manufacturers are reacting to the Pb-free soldering demand by using higher temperature materials such as PEN and PPS. These films are expensive and have voltage limitations. Other approaches include creating a shielded device that allows the use of PET. These approaches are gaining in use today.



Examples of conventional multilayer film reflow results with bare versus shielded construction. Note the 4 minute heat exposure greatly exceeds the typical <30 seconds in most reflow ovens.



Polymer film capacitors offer a high level of stability and reliability in power systems. Future work will continue to reduce package size and make products more suitable for surface mounting. The film makers are busy with developments to increase the working range of film capacitors.