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THE EFFECT OF TEMPERATURE AND VOLTAGE CHANGES ON HIGH VOLTAGE CERAMIC CAPACITORS

Overview

When utilizing ceramic capacitors for circuit design, engineers are generally aware of and where needed, compensate for the effect changes in temperature can have on the capacitance value for certain dielectric types. Of equal importance and often overlooked, is the impact that the application of voltage bias can have on these same dielectrics. This application note reviews the basics for both Temperature and Voltage Coefficient of Capacitance as it relates to common dielectric material types used for high voltage ceramic capacitor designs.

Temperature Coefficient of Capacitance (TCC)

Temperature Coefficient of Capacitance or ΔTC defines the maximum amount by which a capacitance value measured at the reference temperature of +25°C can vary when that same capacitor is subjected to changes in operating temperature. This parameter is dependent upon specific dielectric types.

Class I Dielectrics – Referred to as Temperature Compensating dielectrics these materials are very stable with changes in temperature. Timing or tuning circuits would be a typical application where stability over a wide range of temperatures is critical for proper performance.

EIA-198 provides a summary of the more common Class I dielectrics by outlining the anticipated change in temperature for these materials over an established maximum and minimum operating temperature. (See Table I below)

EIA-198 TC CODES FOR CLASS I CERAMIC DIELECTRICS					
Alpha Symbol	Significant Figure of Temperature Coefficient of Capacitance ppm / °C	Numerical Symbol	Multiplier Applied to Signficant Figure	Alpha Symbol	Tolerance of Temperature Coefficient ±ppm / °C
C	0.0	0	-1	G	30
B	0.3	1	-10	H	60
U	0.8	2	-100	J	120
A	0.9	3	-1000	K	250
M	1.0	4	-10000	L	500
P	1.5	5	+1	M	1000
R	2.2	6	+10	N	2500
S	3.3	7	+100		
T	4.7	8	+1000		
U	7.5	9	+10000		

Table I – EIA-198, Class I ΔTC Designations

Class I dielectrics express ΔTC as a linear curve in ppm/°C (parts per million per degrees Centigrade). Expected shifts in capacitance can be calculated by multiplying the capacitance value at the +25°C by the shift in temperature above or below this reference point and dividing that value by 1,000,000.

Example: For a COG (NPO) capacitor with a measured capacitance of 1000 pF at +25°C, what would be the maximum change in effective capacitance if the actual operating temperature were -55, -0, +85 or +125°C.

$$\Delta \text{ Capacitance @ Operating Temperature} = \frac{\text{Capacitance Value @ +25°C x TCC x } \Delta T}{1{,}000{,}000}$$

$$\Delta \text{ Capacitance @ -55°C} = \frac{1000 \text{ pF x 30 x 80}}{1{,}000{,}000} = \pm 2.4 \text{ pF}$$

$$\Delta \text{ Capacitance @ 0°C} = \frac{1000 \text{ pF x 30 x 25}}{1{,}000{,}000} = \pm 0.75 \text{ pF}$$

$$\Delta \text{ Capacitance @ 85°C} = \frac{1000 \text{ pF x 30 x 60}}{1{,}000{,}000} = \pm 1.8 \text{ pF}$$

$$\Delta \text{ Capacitance @ 125°C} = \frac{1000 \text{ pF x 30 x 100}}{1{,}000{,}000} = \pm 3.0 \text{ pF}$$

From the above calculations it has been determined that a COG (NPO) capacitor that measures 1000 pF at +25°C will measure between 997.6 pF & 1002.4 pF at -55°C, 999.25 pF & 1000.75 pF at 0°C, 998.2 pF & 1001.8 pF at +85°C and 997 pF and 1003 pF at +125°C.

Examples of Class I dielectrics are shown in Table II and graphical representations are shown in Figure I and Figure 2.

| EIA-198 Designation	Significant Figure	Multiplier	Tolerance	Temperature Coefficient ΔTC	Alternate Designation
COG	0	0	±30 ppm / °C	0 ±30 ppm / °C	NPO
U2J	7.5	-100	±120 ppm / °C	-750 ±120 ppm / °C	N750
P3K	1.5	-1000	±500 ppm / °C	-2200 ±500 ppm / °C	N1500
R3L	2.2	-1000	±500 ppm / °C	-2200 ±500 ppm / °C	N2200
T3M	4.7	-1000	±1000 ppm / °C	-2200 ±1000 ppm / °C	N4700
U3N	5.6	-1000	±2500 ppm / °C	-5600 ±2500 ppm / °C	N5600

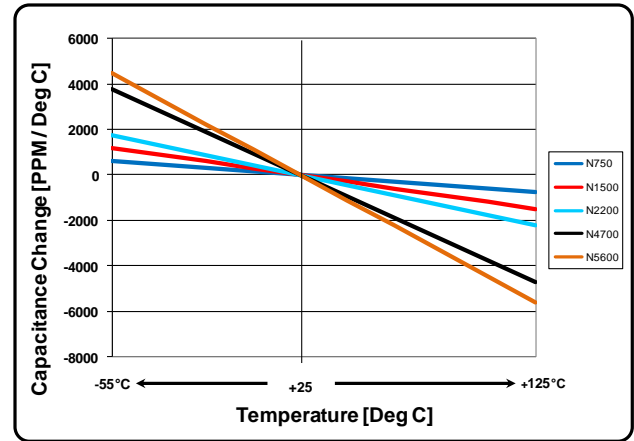Table II – Class I Examples
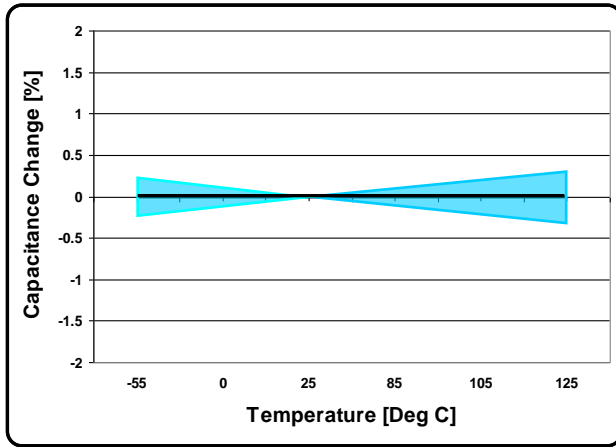
Figure I – ΔTC COG (NPO) Dielectric

Figure II – ΔTC Negative TC Dielectrics

Class II Dielectrics – Dielectric materials that are identified by this classification exhibit stable performance, but certainly not to the same degree as Class I dielectrics. These materials are characterized by a higher dielectric constant, which provides an increase in volumetric efficiency, but their higher temperature coefficient generally limit their use to non precision applications like energy storage, snubbers, decoupling and EMI suppression.

Like Class I dielectrics, EIA-198 also provides a table that identifies the standard designations for Class II Dielectrics. (See Table III)

EIA-198 TC CODES FOR CLASS II, III & IV CERAMIC DIELECTRICS					
Alpha Symbol	Low Temperature °C	Numeric Symbol	High Temperature °C	Alpha Symbol	Max Cap Change Over Temp Range %
Z	+10	2	+45	A	±1.0
Y	-30	4	+65	B	±1.5
X	-55	5	+85	C	±2.2
		6	+105	D	±3.3
		7	+125	E	±4.7
		8	+150	F	±7.5
		9	+200	P	±10
				R	±15
				S	±22
				T	+22 to -33
				U	+22 to -56
				V	+22 to - 82

Table III – EIA-198 Class II ΔTC Designations

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Class II dielectrics exhibit a non-linear ΔTC response, expressed as the maximum possible percentage change that can occur in the +25°C capacitance value, when the subject capacitor is exposed to shifts from the reference temperature to some other point within the materials defined operating temperature range. An X7R dielectric for example is defined as having a maximum ΔTC of ±15% across the operating temperature range of -55 to +125°C. When compared with the 1000 pF, Class I, COG (NPO) capacitor that exhibits a worst case shift in capacitance of -2.4 pF (997.6 pF minimum) at -55°C and +3 pF (1003 pF maximum) at +125°C, a 1000 pF capacitor manufactured with Class II, X7R dielectric can exhibit a worst case shift in capacitance of ± 150 pF or somewhere between 850 and 1150 pF at any point across minimum to maximum operating temperature range.

Another important point worth considering is that although dielectrics may be categorized by the same EIA designation (ie. X7R), the actual shape of the ΔTC curve and the temperatures at which the maximum shift occurs, may be different. One X7R dielectric for example, may only exhibit a change in capacitance of ±10%, with that maximum shift occurring at temperature A, whereas another X7R dielectric may exhibit a shift in capacitance that encompasses the entire allowable limit of ±15%, with capacitance extremes occurring at temperature B.

Examples of common Class II dielectrics are shown in Table IV and a graphical representation is shown in Figure II.

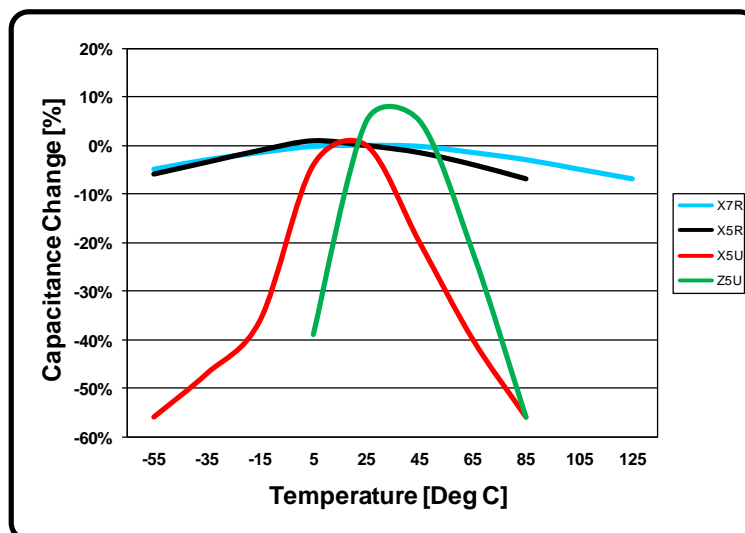| EIA-198 Designation	Minimum Temperature Symbol	Mimimum Operating Temperature	Maximum Temperature Symbol	Maximum Operating Temperature	Temperature Coefficient ΔTC
X5R	X	-55 °C	5	+85 °C	±15%
X7R	X	-55 °C	7	+125 °C	±15%
Y5V	Y	-30 °C	5	+125 °C	+22 / -82%
Z5U	Z	+10 °C	5	+125 °C	+22 / -56%

Table IV – Class II Examples

Figure III – ΔTC Class II Dielectrics

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‡ Special ΔTC Considerations – The majority of examples offered in the previous sections deal with capacitors intended for use in the -55 to +125°C operating range. There are however several EIA-198, Class II designations that classify dielectrics for use well beyond the +125°C maximum. X8R and X9R materials for example, are similar to X7R, inasmuch as they limit their maximum ΔTC to ±15%, but they are intended for use up to +150 and +200°C. In addition, several manufacturers have developed their own unique Class II, high temperature formulations that are not defined by EIA-198.

As for Class I dielectrics, COG (NPO) is an excellent example of a dielectric that is routinely employed in higher temperature applications. The linear characteristics of its ΔTC curve extend well beyond the +125°C limit and this material has been successfully employed in applications where ambient temperatures approach temperature extremes in the +250°C range and higher. Figures IV and V illustrate ΔTC performance for a Class I, COG and some Class II dielectrics when exposed to higher temperatures.
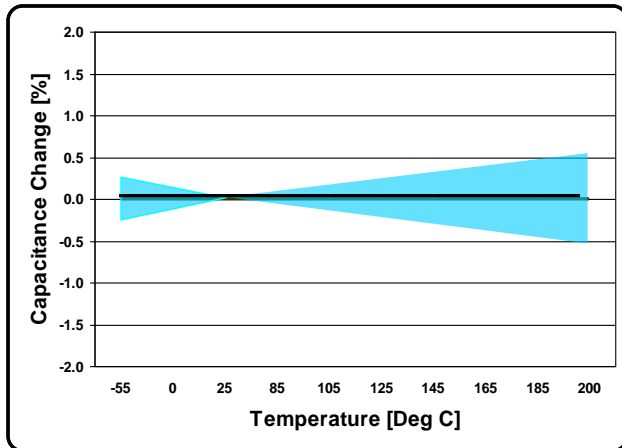

Figure IV – ΔTC HTNPO
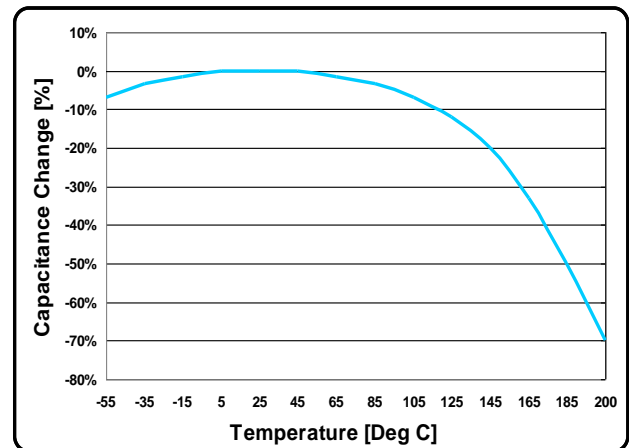

Figure V – ΔTC HTX7R

It is important to note that ΔTC is not the only performance characteristic to consider when choosing a capacitor for high temperature applications. One should expect to see a further degradation in the insulation resistance / leakage current characteristics of these dielectrics to the point where some dielectrics may be unable to maintain a charge. There are several other performance characteristics that may be affected including dissipation factor and equivalent series resistance.

Voltage Coefficient of Capacitance (VCC)

Another aspect of capacitor behavior that is often overlooked is the affect that the application of voltage can have on the capacitance of the device. Referred to as Voltage Coefficient of Capacitance (VCC) or ΔVC, this functional characteristic quantifies the maximum change in capacitance that one might expect to see when the capacitor is exposed to various voltage levels. Capacitance testing is typically performed at 1± 0.2 VRMS, which is extremely low in comparison to the typical working voltages encountered during actual operating conditions. At this test voltage, the effect on capacitance is negligible, but for certain dielectric types like those defined by EIA-198, Class II materials, exposure to higher DC operating voltages can result in a significant loss in effective capacitance.

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In very simple terms, dielectrics manufactured with Class I formulations show little sensitivity to AC or DC voltage. Class II ferroelectric bodies on the other hand, exhibit a shift in their dielectric constant when exposed to these same AC and DC voltages and this can result in a rather significant capacitance variation from their original test value. The amount of change is dependent on the type of dielectric material being used and the level of voltage stress applied across the dielectric. Higher K dielectrics tend to exhibit the largest shift in ΔVC and in worst case situations where the capacitor is exposed to an increased voltage stress, the user may experience as much as a 60 to 65% loss, or more.

⚏ Class II Dielectrics – This class of dielectrics respond differently than Class I dielectrics when subjected to either AC or DC voltages. When exposed to AC, these dielectrics exhibit an increase in dielectric constant (K) and a subsequent increase in capacitance. As the AC voltage is increased, the K value increases, with higher K dielectrics exhibiting the largest swing. This positive shift continues until a material specific voltage limit is reached, at which point the trend reverses and the dielectric constant / capacitance value starts to decline.

When exposed to DC bias, Class II dielectrics tend to exhibit a decrease in dielectric constant, with the higher K dielectrics again exhibiting the largest shift. The amount of voltage applied can also impact the amount of capacitance lost, but it is important to understand that relationship between voltage and capacitance has less to do with voltage level and much more to do with the dielectric thickness and the resulting volts per mil stress applied. Essentially, two capacitors with identical capacitance values and voltage ratings, manufactured with the same dielectric material can, depending on their internal construction, exhibit totally different capacitance values when biased at the same working voltage. One can't assume therefore that a 1 µF, 100 VDC, X7R capacitor purchased from Vendor A will behave exactly the same as a 1 µF, 100 VDC, X7R capacitor purchased from Vendor B.

Example: Two capacitor manufactures produce 1.0 µF, 100 VDC capacitors using the same X7R dielectric formulation. Vendor A designs the part with a dielectric thickness of 1.5 mils, while Vendor B designs their alternative design with a dielectric thickness of 1.0 mils. If both designs are subjected to the full maximum operating voltage of 100 VDC, what would be the resulting ΔVC for both designs.

$$\text{Voltage Stress} = \frac{\text{Operating Voltage}}{\text{Dielectric Thickness}}$$

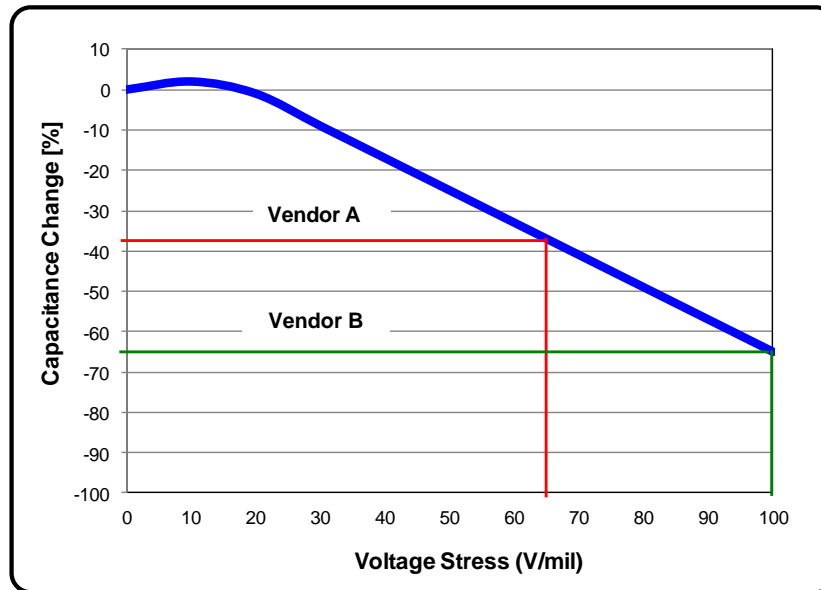| **Vendor A**		**Vendor B**	
Voltage Stress =	$\dfrac{100 \text{ Vdc}}{1.5 \text{ mils}}$	**Voltage Stress** =	$\dfrac{100 \text{ Vdc}}{1.0 \text{ mils}}$
=	66.67 volts / mil	=	100 volts / mil
Voltage Coefficient = (From Figure VI)	-38%	**Voltage Coefficient** = (From Figure VI)	-65%
Actual Capacitance = (@ 100 Vdc)	1.0 µF x (1 - 0.38)	**Actual Capacitance** = (@ 100 Vdc)	1.0 µF x (1 - 0.65)
=	**0.62 µF**	=	**0.35 µF**

Figure VI – Voltage Coefficient vs Volts / Mil

Voltage – Temperature Coefficient of Capacitance (VTC)

It is important to recognize that ΔTC and ΔVC are in fact additive components and that a change in both operating temperature and working voltage or combinations thereof, will have a cumulative effect on the overall performance of the capacitor. As an example, let's re-examine the 1.0 µF,100 Vdc, X7R capacitor from the previous section that was manufactured with 1.0 mil dielectric. We know that for elevated levels in WVDC there will be a loss in capacitance and that at 100 V/mil the ΔVC for this particular capacitor will be -65%. If we now consider that the actual operating temperature is something other than +25°C and that at this temperature the ΔTC is -15%, then we need to recognize that the overall loss in capacitance or ΔVTC, can be as much as -80%.

Military specifications like MIL-PRF-49467 have evened the playing field for suppliers inasmuch as they have defined a series of dielectric subcategories that limit the amount of capacitance loss that a capacitor can exhibit due to changes in both temperature and voltage. This is most often done by utilizing an X7R formulation with a ΔTC that is well within the allowable ±15% and limiting the ΔVC through a reduction in the volts per mil stress across the dielectric. BX is one such dielectric where the maximum ΔVTC is defined as +15 / -25% across the entire operating temperature range of -55 to +125°C. Other options and their corresponding ΔVTC limits are listed in Table V.

Military Symbol	Voltage - Temperature Coefficient
BX	+15 / -25% @ WVDC & -55 to +125°C
BR	+15 / -40% @ WVDC & -55 to +125°C
BZ	+15 / -45% @ 60% WVDC & -55 to +125°C
BQ	+15 / -50% @ WVDC & -55 to +125°C

Table V - Capacitance Change With Respect to +25°C

Conclusions

When utilizing ceramic capacitors it is important to consider that Class II and Class III dielectrics can exhibit a significant loss in capacitance when operated at high voltage levels and at varying temperatures within their operating temperature range. One should also recognize that capacitor manufacturers may not necessarily utilize the same dielectric formulations and that those choices, along with differences in internal construction, can also impact the characteristics of the device. With that in mind, if there is ever a concern that changes in capacitance can have an effect on system performance, customers should always ask their potential supplier questions regarding specific performance characteristics of the capacitor they are being offered.

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