

New High Temperature Ceramic Capacitor

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Abstract:

The need for ceramic capacitors with optimal electrical performance at high temperature, 200°C and above has grown in recent years. A novel ceramic provides excellent electrical characteristics over the temperature range 200°C to 350°C. It is found to have a dielectric constant of 4000 across this high temperature range. This paper discusses electrical parameters and the reliability performance of this ceramic, including a dissipation factor of <1%, from 200°C to 350°C. Life test results at high temperatures are demonstrated.

Introduction:

The requirement for a multilayer ceramic capacitor (MLCC) capable of continuous operation at temperatures of 200°C and higher has existed for some time. One such application is in instrumentation used in down-hole measurements of oil/gas and geothermal wells. In the past few years the demand for oil has driven producers to tap deeper and deeper deposits. Deeper deposits mean higher operating temperatures. For many years the norm was 150°C. Now, many tools are required to perform at 175°C to 200°C. There is also active development for tools that will operate up to 250°C. It is not difficult to imagine operation at 275°C to 300°C in a year's time. Temperatures in geothermal wells can reach 400°C, with 325°C being the typical maximum. These MLCC's may need to operate for up to five years at these temperatures if used in the control system of geothermal wells (1). However, the market for MLCC's for use in this application is limited.

Other high temperature applications for MLCC's include aviation and automotive. For aviation systems, equipment is being designed to operate at temperatures of 300°C, or higher (2). Automotive applications, while severe, may not have temperature requirements as high as those in down-hole or aviation applications. Engine and transmission temperatures are typically less than 200°C. For wheel mounted components, such as those in ABS sensors, the temperatures can range from 150°C to 250°C, but less than 300°C (3). Most automotive

applications are typically less than 150°C as evidenced by recent patent applications (4, 5) that specifically mention automotive as one of the intended applications.

There are several on going efforts to develop high-temperature ceramic capacitors capable of meeting the operating temperature requirements required for down-hole, aviation and automotive applications. The primary efforts appear to be directed at automotive applications since this market is much larger than either of the other two markets mentioned.

A review of what products are currently available shows that most offerings are for ceramic capacitors designed to operate at maximum temperatures of either 150°C or 200°C. If the capacitors are EIA Class II, the capacitance drop off at 200°C can be as high as 45%. An early effort to develop a ceramic dielectric capable of operating at 200°C was a lanthanum-modified lead zirconate titanate (PLZT) developed by the late Dr. Galeb H. Maher (6, 7, 8, 9). This dielectric system showed considerably less variation in capacitance at 200°C than barium titanate based dielectric systems (10). Capacitors built with this PLZT dielectric formulation met the EIA characteristic X9S (-55°C to 200°C, $\Delta C \pm 22\%$).

On going efforts by manufacturers of MLCC, suppliers of ceramic dielectric formulations and universities continue to work towards developing high temperature ($> 200^\circ\text{C}$) dielectric formulations. This work is focused on systems such as barium titanate-barium scandium oxide, bismuth metal oxide-lead titanate and others. Performance characteristics for high temperature ceramic capacitors with operating temperatures ranging from 150°C to over 450°C are shown on TRS Technologies' website (11). These dielectrics were developed for characteristics similar to Y5V except the peak capacitance is shifted from a temperature range of 10°C to 40°C to temperature ranges of 150°C to 350°C or 300°C to 500°C. This paper reports on a capacitor built with a proprietary dielectric formulation designed to operate over a broad temperature range of 200°C to 350°C with a dielectric constant that is essentially flat at these temperatures.

Experimental:

Evaluated in this study were multilayer ceramic chip capacitors built with a tape casting system in a standard EIA 0805 chip size. These capacitors were built using a proprietary dielectric formulation and had a nominal room temperature capacitance value of 0.004 μF and were rated at 12 Vdc. The design of these capacitors was 10 layers of active dielectric at 0.8 mils thick. All of the capacitors were tested at room temperature for the following electrical parameters:

- Initial capacitance and dissipation factor at 1 Vrms and 1 KHz
- Dielectric withstanding voltage at 2.5 times rated DC voltage (30 Vdc)
- Insulation resistance at rated DC voltage (12 Vdc)

A matrix of seven groups of these capacitors was life tested according to the following:

Temperature °C	Test Voltages		
	12 Vdc	25 Vdc	50 Vdc
250			*
300	*	*	*
350	*	*	*

The leakage current of each MLCC was monitored during the test by measuring the voltage across a 100 K Ω resistor in series with the capacitor. A capacitor was considered a failure when there was a 50% increase of voltage across the resistor.

In addition to the life test matrix, various other electrical parameters were measured to provide a better understanding of the performance of this new, high temperature ceramic dielectric. The parameters measured include:

- The variation of capacitance and dissipation factor with temperature.
- Leakage current as a function of temperature.
- Variation of capacitance with DC voltage and temperature.
- Ultimate breakdown voltage.

Results and Discussion:

Results of the initial electrical tests follow:

Capacitance @ 1 KHz and 1 Vrms	0.004 \pm .0002 μ F
Dissipation Factor @ 1 KHz & 1 Vrms	4.5 \pm 0.1 %
DC Flash (30 Vdc)	0 failures
Insulation Resistance (12 Vdc)	160 G Ω

The variation of dielectric constant with temperatures between -55°C and 350°C is shown in Figure 1. As can be seen from this curve, the dielectric constant increases rather sharply from -55°C to 150°C, at which point it is essentially flat, increasing slightly to 300°C. Above 300°C it begins to drop off as it approaches 350°C. However from 150°C to 350°C the dielectric constant does not drop below 3500.

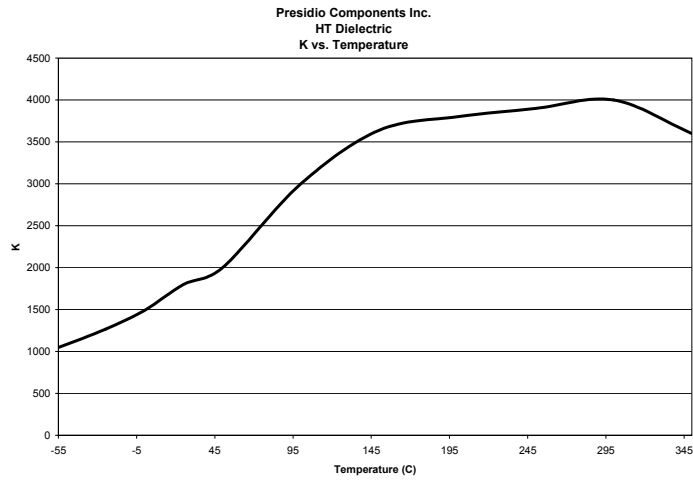


Figure 1. Variation of dielectric constant with temperature measured at 1 KHz and 1 Vrms.

The dissipation factor as a function of temperature is shown in Figure 2. From a maximum value of 4.8% at room temperature, the dissipation factor decreases very rapidly with increased temperature reaching a minimum value of less than 0.2% at 200°C before it increases slightly to 0.4% at 350°C.

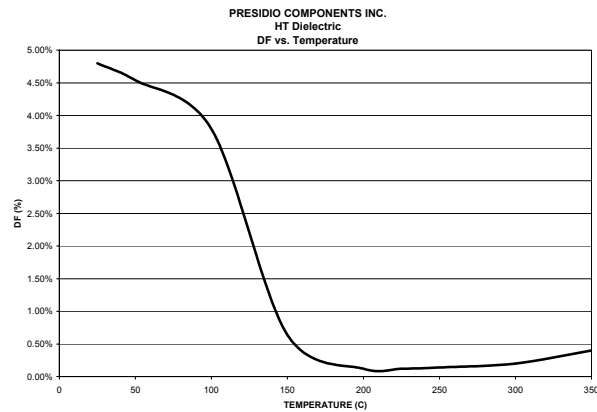


Figure 2. Variation of the dissipation factor with temperature when measured at 1 KHz and 1 Vrms.

The leakage current as a function of temperature is shown in Figure 3. The RC (ΩF) product is shown in Figure 4. For temperatures above 125°C, there is no industry requirement for

what the insulation resistance should be. Therefore, if the same reasoning is used for this paper that was used in a previously referenced paper (10) on a PLZT dielectric system for use at 200°C the RC (Ω F) product at 350°C should be .001 Ω F's. This value was arrived at by taking one tenth of the insulation resistance requirement from the previous temperature as shown in the following table:

Temperature °C	Insulation Resistance Ω F
25	1,000
125	100
150	100
200	10
250	1.0
300	0.1
350	0.01

This does not seem like a viable approach to determining what the insulation resistance should be at the temperatures of interest. This value will probably have to be determined empirically. It will all depend on what the maximum leakage current can be for the circuit to still function as designed. As can be seen from Figure 3, the maximum leakage current is less than 1.0 μ A at 350°C. The RC product at 350°C is 0.37 $M\Omega$ - μ F, which is two magnitudes greater than the theoretical RC product determined in the table above.

Samples were tested for the ultimate breakdown voltage (UBV) at room temperature. Each MLCC was flashed starting at 50 Vdc and continued to slowly increase the voltage until the sample failed. The current was limited to 50 milli-amperes. The average breakdown voltage was 612 Vdc, with the minimum breakdown voltage 588 Vdc and the maximum breakdown voltage 630 Vdc.

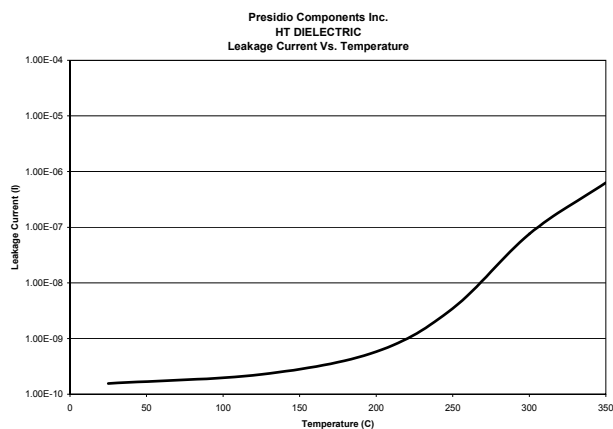


Figure 3. Variation of leakage current over the temperature range of 25C to 350C.

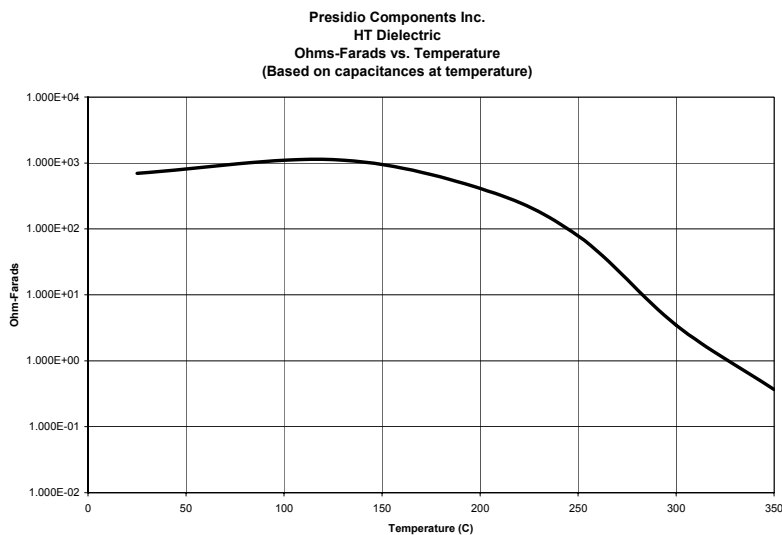


Figure 4. Variation of the RC time constant over the temperature range of 25C to 350C.

The variation of capacitance and dissipation factor with temperature with 0 Vdc and 20 Vdc applied bias, measured at 1 KHz and 1 Vrms. The capacitance remained nearly constant over the entire temperature range of 25°C to 350°C. The maximum change in capacitance between 0 Vdc bias and 20 Vdc bias appears to have occurred at 275°C and is less than 5%. The dissipation factor also exhibited a small change between 0 Vdc and 20 Vdc bias in the temperature range of 25°C to approximately 175°C. Above 175°C the dissipation factor is essentially constant with the applied bias having no effect.

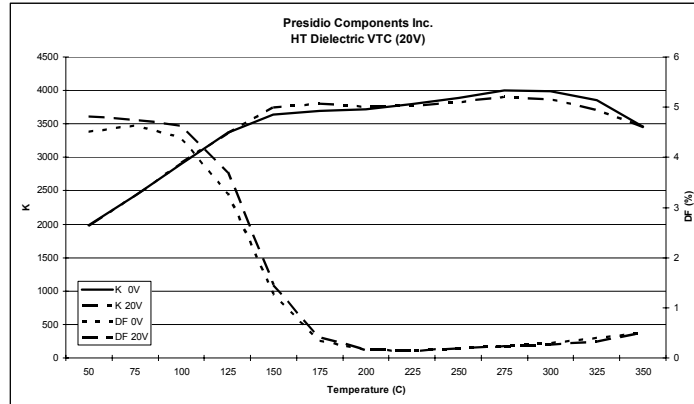


Figure 5. Variation of capacitance and dissipation factor with temperature and applied DC bias measured at 1 KHz and 1 Vrms.

In Figure 6, the variations of the dielectric constants are compared for a formulation that meets the Military BX requirements (ΔT -55C to +125C, $\Delta C \pm 15\%$ with 0 Vdc bias, $\Delta C +15\%$, -25% with rated Vdc bias), one that meets the EAI X7R requirements (ΔT -55C to +125C, $\Delta C \pm 15\%$) and this new high temperature (HT) dielectric formulation for which there are no industry standard requirements. As can be seen, both the X7R and BX dielectric constants relatively high and flat over the temperature range from -55C to +125C compared to the HT dielectric constant which is increasing rather sharply. Above 125C both the BX and X7R dielectric constants drop sharply to 200C after which they continue to drop at less of a rate to 350C. The HT dielectric constant continues to rise to 150C at which point it is essentially constant to 350C.

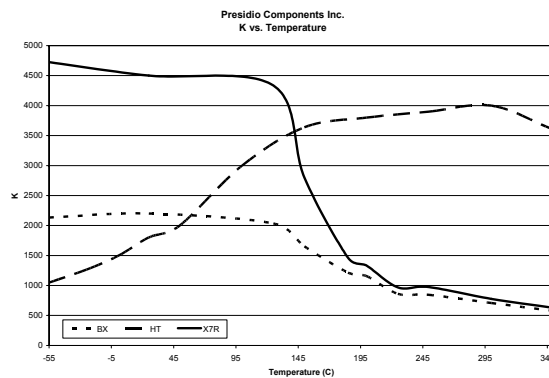


Figure 6. Variation of capacitance over the temperature range of -55C to 350C for a BX, X7R and the HT dielectric formulations.

Summary:

The electrical properties of a new, high temperature proprietary dielectric system are presented.

- The variation of dielectric constant is essentially flat over the temperature range of 150°C to 350°C.
- The dissipation factor is less than 0.5% above 160°C.
- The ultimate breakdown voltage of these capacitors is 612 Vdc.
- The capacitance with and without bias voltage is nearly constant over the entire temperature range of 25°C to 350°C.
- The bias voltage has essentially no effect on the dissipation factor for temperatures above 175°C.

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