Current Handling in Multi-Layer Ceramic Capacitors

Abstract: A reasonable and not uncommon inquiry regarding a multi-layer ceramic capacitor is, How much current can it handle? Some vendors attempt to address this question by providing a typical maximum current vs. frequency curve divided into two segments: one “voltage limited” where the peaks of the RF voltage equal the rated WVDC and a second “thermally limited,” where the dissipated heat creates a capacitor temperature equal to its maximum rating. This application note examines and seeks to elucidate the basis for this approach, along with its fundamental assumptions, omissions, and inconsistencies.

Current Handling in Multi-Layer Ceramic Capacitors

Introduction. On first glance, it might seem like the term "current handling" as applied to an MLCC is fairly straightforward, e.g., a customer asks, "What is the maximum current I can safely put through this device?" But the response from a PPI engineer would, first, likely be a series of questions: "Well, at what frequencies will you be operating? Will there be a DC voltage across the device in addition to the RF voltage that's creating the current? Is operation CW or pulsed and, if the latter, what are the pulse parameters (width, rise time, duty cycle)? What is the nature of the thermal environment, e.g., conductive cooling and/or convective cooling (air flow), and what are the thermal resistances to a heat sink on each edge of the MLCC? And" – finally, but perhaps most cogently(!) – "what are your requirements for maximum change in capacitance value, DF (dissipation factor), and IR (insulation resistance) over a specified time interval of operation?"

In this application note, we'll try to at least address the above issues, and so the reader is asked for some patience while we present brief reviews of Reliability and Voltage Degradation, before proceeding to a more extended discussion of the main subject, Current Handling. As suggested in the first paragraph, it is our thesis that these topics are inextricably interwoven, and that no one makes sense without consideration of the others.

Section I: Reliability

Review of Theory: Constant Failure Rate.

Discussions of reliability often start with the so-called "bathtub" curve, which describes the failure rate of electronic equipment; it is shown in **Fig. 1.**

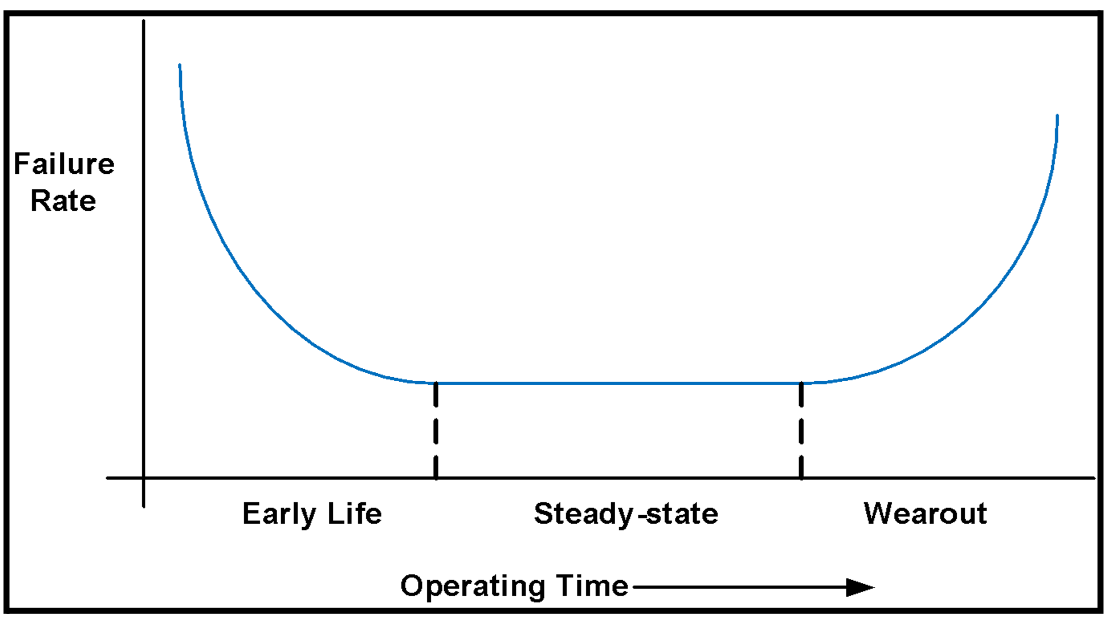


Fig. 1 The 'bathtub curve"

The Early Life or "Infant Mortality" segment models failures generally resulting from manufacturing process imperfections, material defects, and damages in handling -- some controllable, some not. Failures in the Steady-State period typically result from either random events (e.g., in the case of memory chips, cosmic ray impacts) or various infant mortality mechanisms that are sufficiently spread out in time that they appear to be random. The final curve portion, the so-called Wear-Out stage, results from fundamental physical limitations of the materials and interfaces.

The instantaneous failure rate, λ(t) – also known as the hazard rate -- is defined as the rate of change of the cumulative failure probability divided by the probability that a unit will not already have failed by time t. If the cumulative fraction of failures from time T = 0 to T= t is denoted by F(t), the hazard rate is

$$\lambda(t) = \frac{dF(t))/dt}{1-F(t)} \tag{1}$$

We focus in this section on the steady-state portion of the curve, the area where the failure rate is approximately constant. It is usually expressed as % failures per 1000 hours at maximum rated conditions, i.e. the highest steady-state DC voltage and temperature, or FITs, failures per billion hours.

Note that "failure," needs to be specifically defined; it is usually specified as a maximum allowable change in certain parameters, e.g., capacitance, dissipation factor (DF), insulation resistance (IR), after the units under test are exposed to particular DC voltages and temperatures over certain time periods. Since failure rate is a random variable, its value, in general, will differ from test to test, i.e., the failure rate of any particular population sample will, in general, differ from the failure rate of the entire population.

When a population sample is measured for reliability, the "raw" failure rate is simply r, the total number of failures divided by the number of component-hours, i.e.,

$$\lambda_{RAW} = \frac{r}{NT} \tag{2}$$

Where r = total number of failures
N = number of components tested
T = test duration in hours

Let us now consider the constant failure rate region of the bathtub curve: Using the classical statistics approach, we must replace the number of failures in (2) by the argument of a probability distribution, chi-square, divided by 2, i.e.,

$$r \sim \frac{\chi^2_{\alpha,2r+2}}{2} \tag{3}$$

Here, r = total number of observed failures, as before
α = acceptable risk of error
1 - α = confidence level

and $\chi^2_{\alpha,2r+2}$ is the argument (x-axis value) of a chi-square cumulative distribution function that has a probability of (1 – α) percent and 2r +2 degrees of freedom.

There are a number of nuances and subtleties regarding the chi-square distribution that are beyond the scope of this paper. For the interested reader, [11] and [12] are good starting points for further insights.

The reliability of an MLCC can then be expressed as the product of the statistical model parameters above and the acceleration functions or "stress factors" resulting from electrical and thermal conditions, as given in (4), (5), and (6) herein. Taking into account all the above, the classical statistics formula for λ_{ss} is

$$\lambda_{SS} = \frac{\chi^2_{\alpha,2r+2}\, x\, 10^9}{2NT\pi_S\pi_T} \qquad (4)$$

Where λ_{SS} = failure rate in FITs
$\chi^2_{\alpha,2r+2}$ = the chi-squared cumulative distribution argument
π_S = electrical acceleration factor
π_T = thermal acceleration factor

The meaning of (4) is that, if a large number of sample populations were measured, approximately (1-α) percent would have $\leq$ r failures.

The temperature acceleration factor is most often considered to follow the Arrhenius equation:

$$\pi_T = e^{\frac{E_a}{k}\left[\frac{1}{T_0} - \frac{1}{T_1}\right]} \qquad (5)$$

where T_0 = reference temperature in ^{0}k
T_1 = operating temperature in ^{0}k
Ea = activation energy in eV
K = Boltzmann constant = 8.62 x 10^{-5} eV/^{0}k

For precious-metal-electrode (PME) capacitors with a magnesium titanate dielectric, such as the PPI 3838C series, a value for Ea of about 1.0 eV is generally accepted. In contrast, for base-metal-electrode (BME) capacitors with barium titanate dielectrics, e.g. the PPI 0201BB series, typical Ea values range from 1.1 to 1.5 eV. **Fig. 2** shows the variation of π_T with temperature for two values of Ea; the operating temperature has been taken as 55 ^{0}C.

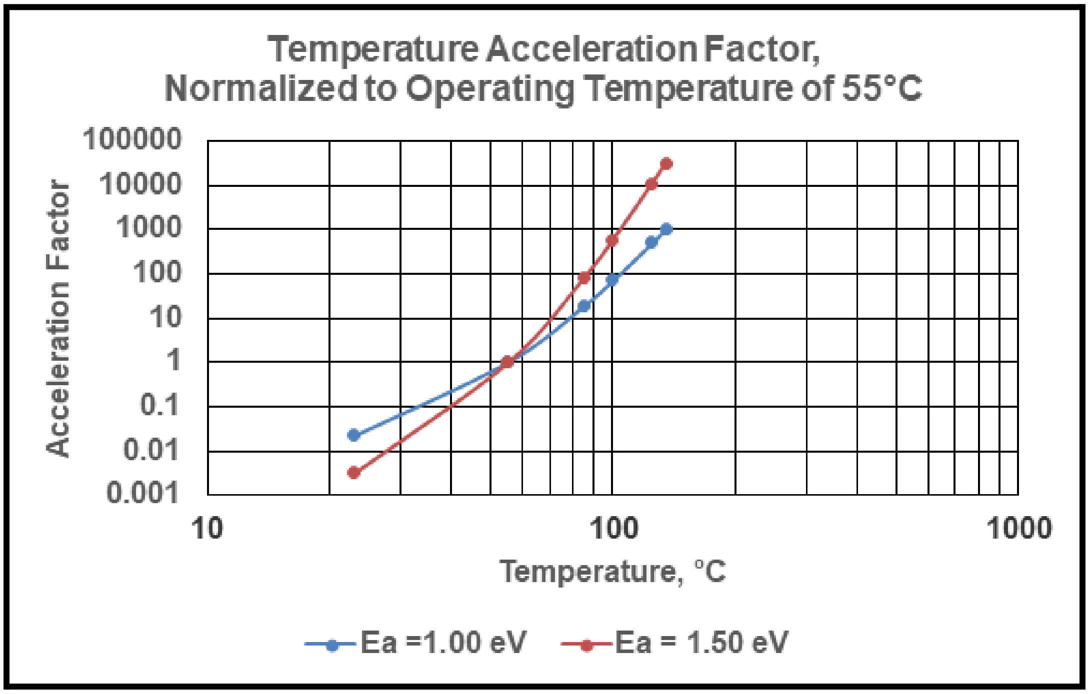


Fig. 2 Temperature acceleration factor vs. temperature, T_0 taken as 55°C (328 K)

Because of its exponential dependency, the temperature acceleration factor is immensely strong. Note, for instance, that for an Ea = 1.00 eV, the expected lifetime at 125°C is about 500 times less than that at 55°C. For an Ea = 1.50 eV the situation is even worse: The expected lifetime at 125°C is about 11,177 times less than that at 55°C! (Hint: Could this be why we might be concerned about the heating effect of RF current?)

The voltage acceleration factor is most often considered to follow a power law:

$$\pi_s = \left(\frac{V_1}{V_0}\right)^N \tag{6}$$

where V_0 = reference voltage
V_1 = operating voltage
N = a characteristic exponent

For PME capacitors, a value for N of 2.9-3.0 is generally accepted -- e.g., 3.0 is specified in MIL-PRF-55681G -- and so the failure rate at a given temperature varies with the cube of applied voltage. For BME capacitors, N values ranging from 1.5 to 7.1 have been reported in the literature. **Fig. 3** shows the variation of π_s with voltage ratio for two values of N.

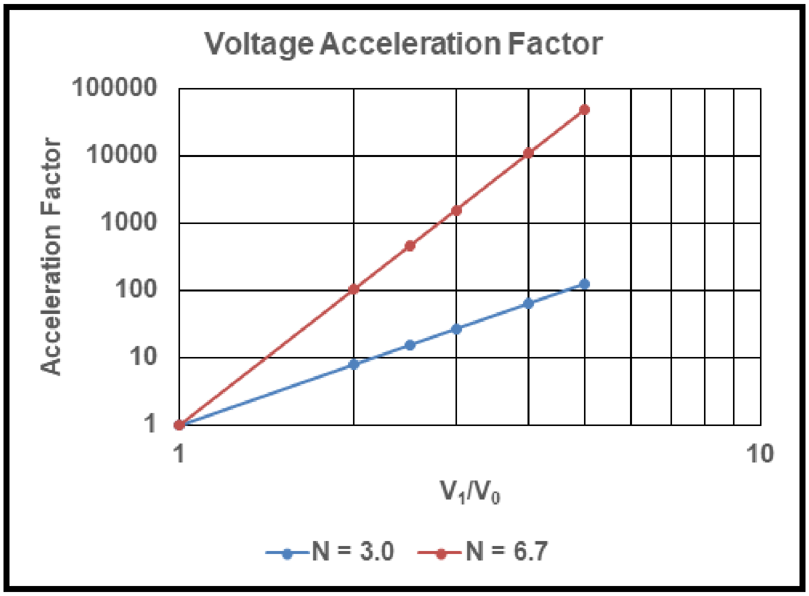


Fig. 3 Voltage acceleration factor vs. voltage ratio

The relationship of "the working voltage DC" (WVDC) and steady-state failure rate at a given temperature is thus defined by equations (1) - (6). Among the cogent take-aways from the above formulas and discussion are:

- Failure rate always increases with higher applied voltages and higher temperatures.
- If only constant failure rates are considered -- i.e., if infant mortality failures are assumed eliminated by voltage conditioning and wear-out failures are assumed to occur at times far greater than any that would cause concern -- a WVDC rating can be chosen to provide a particular maximum (constant) failure rate at a particular temperature.
- "Failure" needs to be specifically defined, typically as the maximum allowable change in certain parameters within certain time periods.
- A WVDC rating without also specifying the definition of "failure," as well as the associated constant failure rate, confidence factor, and operating temperature is meaningless.

Thus, one definition of the term **"WVDC rating" is: The highest DC voltage that can be continuously applied to a device at temperatures up to a certain maximum and have the device meet particular failure-rate criteria (maximum change of certain electrical parameters) at a particular confidence level, as determined by measurements on a given minimum sample-size for a specified period of time.**

In the next section, we discuss non-constant failure rates.

Review of Theory: Non-constant Failure Rates and Cumulative Percent Failures.

The assumption of a constant failure rate to characterize MLCCs is convenient, leads to the simple calculations shown in (1) – (6), and is used by most capacitor manufacturers. However, that characterization assumes that early lifetime failures have been largely weeded out (e.g., by voltage conditioning, aka "burn-in") and that wear-out failures occur so far beyond the useful component life that they can be disregarded. Unfortunately, for many thin-layer, base-metal electrode capacitors, such as those in PPI's broadband line, these assumptions are not necessarily correct. For COTS product, in general, there is no voltage conditioning performed on every part and, depending on voltage and thermal operating stress, wear-out may well occur within a customer's expected useful lifetime. For these cases and, in fact, for any segment of the bathtub curve, there is a very flexible expression that can be fit to the data points: the Weibull characteristic.

The 2-parameter Weibull cumulative distribution function (cdf), the cumulative probability of failure at time t (or *unreliability function*), is given by

$$F(t) = 1 - e^{-(t/\eta)^{\beta}} \tag{7}$$

Here, η is a scale parameter -- the time at which 63.2% of the population has failed -- and β is a dimensionless shape parameter that defines the shape of the curve and whose value is often characteristic of the failure mode under study. By re-arranging (7), and successively taking the natural logarithms of both sides, one can convert it to a linear form such that

$$y = \beta x - \beta \ln ln\,(\eta) \tag{8}$$

where x = ln (t)
y = ln(ln(1/(1- F(t)))

Thus, as illustrated in **Fig. 4,** if we plot the cumulative percent failures vs. time on a graph with log-log scales (in this case with a base 10), they will lie, in most cases, on a straight line, thereby indicating their conformity to a Weibull distribution. The slope of the line is β.

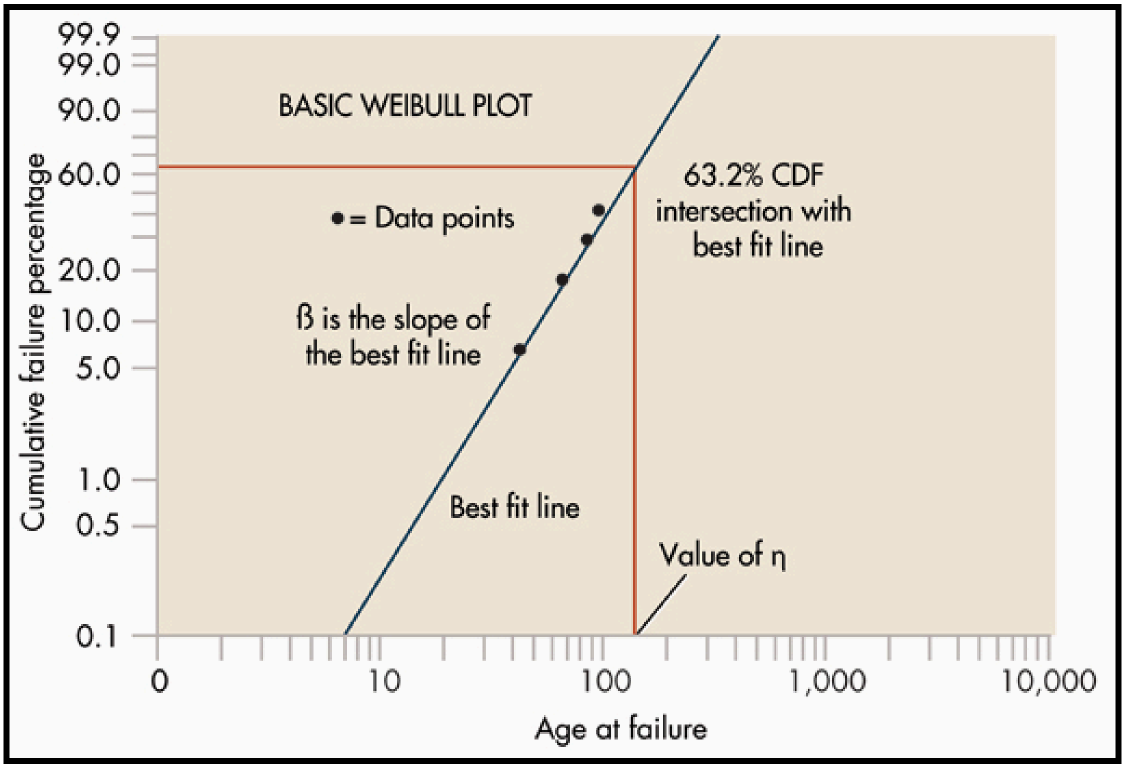


Fig. 4 Basic Weibull plot

The failure rate is given by

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \quad (9)$$

Note that if:

- β=1, the failure rate reduces to a constant, β/η
- If β <1, the failure rate decreases with time
- if β > 1, the failure rate increases with time

It is these properties that enable Weibull functions to be fit to all portions of the bathtub curve.

The MTTF of the population is given by

$$MTTF = \eta\Gamma(1 + \frac{1}{\beta}) \quad (10)$$

where Γ(x) is the gamma function of x

Unlike when the reliability is a constant, however, the uncertainty bounds of the MTTF for the general Weibull distribution is complicated to compute; "maximum-likelihood," Fisher Matrix, and other methodologies beyond the scope of this paper are used to do so. (See [13] for a more extensive discussion.) Note that when β=1, the failure rate reduces to 1/η, and the MTTF = η.

Knowledge of η and β also enable us to calculate the time at which a given percentage of the population will have failed, or the so-called "BX% life":

$$BX\%\ life = \eta\{-Ln[R(x\%)]\}1/\beta \quad (11)$$

where $R(x\%) = 1 - \%failures/100$

Even for constant failure rate assumptions, the BX% life is very useful for determining when a given percentage of the parts – other than the 63.2% characterized by the MTTF -- are likely to fail. **Table 1** shows the calculated BX% life for PPI 0708N MLCCs operated at rated voltage (500 VDC) and various temperatures, assuming a constant failure rate and a 90% confidence level.

Temp.	MTTF, hrs. @ Conf. Level	MTTF, yrs. @ Conf. Level	FITs	1% Life (yrs.)	0.1% Life (yrs.)
175	1.74E+05	19.9	5757	0.200	0.0199
150	8.03E+05	91.9	1246	0.924	0.0920
125	4.50E+06	515	222	5.177	0.5154
110	1.41E+07	1614	71	16.221	1.6148
100	3.17E+07	3629	32	36.469	3.6305

Table 1 0708N calculated MTTFs, failure rates, and BX% life vs. temperature

Note that the results can sometimes be surprising; what might seem a relatively low failure rate, 1246 FITs (failures per billion hours), or an MTTF of 91.9 years, nevertheless results in 1% of the parts failing in just under a year.

In light of the above, we can formulate another possible definition of WVDC as an alternative to the one offered under **Fig. 3**: **WVDC is the applied DC voltage at which a specified maximum percentage of parts are expected to fail after a given operating time at a particular temperature and with a specified confidence level.** Unfortunately, while this would be a useful definition and metric, it is virtually never offered or spelled out on MLCC data sheets.

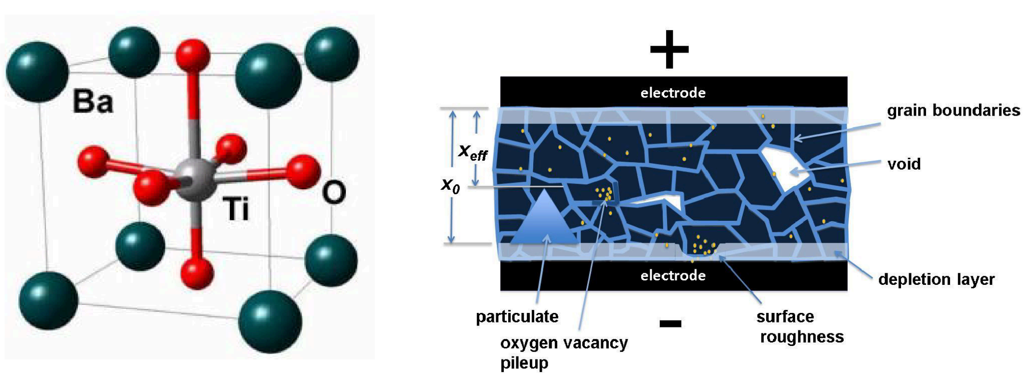
With the above background and caveats regarding reliability, we are now ready to examine more fully exactly what may happen to an MLCC when each of the following electrical stressors is applied: a high DC voltage, a high AC or RF voltage, and/or a high current.

Section II: Failures and Degradation Resulting from Applied Voltages

DC Voltage Failures. The failure of an MLCC, that is, the degradation of one or more performance parameters by some defined amount, can be caused by many different mechanisms, and may be abrupt or gradual, internal or external.

Internal avalanche breakdown is typically abrupt and results from some form of charge multiplication, e.g. an avalanche that leads to a high-temperature plasma or arc. It most often occurs at high voltages and is caused by such extrinsic imperfections in the dielectric as porosity, presence of foreign materials, de-laminations, and cracks. Additional exogenous contributors are microscopic irregularities on the electrode surfaces and edges or insufficient rounding of the electrode corners that act to concentrate the electric field.

Gradual degradation is characterized by a continual increase in leakage current that leads to self-heating and eventual failure [5]; hence, its sometime designation as "thermal runaway." It most often occurs at high temperatures and results from such intrinsic imperfections as electronic disorders, dislocations, and grain boundaries. While PME (Precious Metal Electrode) capacitors generally display avalanche failures, BME (Base Metal Electrode) devices exhibit both types of failures. The physics in the latter is quite complicated and involves increased charge injection under the stress of voltage and temperature. The dominant mechanism for BME MLCCs has been identified as migration of "oxygen vacancies" within the ceramic crystalline structure [4]. The latter is typically a tetragonal arrangement of a barium ion centered within a lattice of titanium and oxygen ions. (Hence, the ceramic formula, $BaTiO_3$.) In some of the crystals, an oxygen ion is missing and creates a positively charged "vacancy" which, under the influence of an applied electric field, appears to move through the ceramic in a manner analogous to holes moving through a semiconductor. (See Figs. 5a and 5b, taken from [7] and [8] respectively.) Final breakdown is believed to occur when these vacancies accumulate on oppositely charged electrodes and/or ceramic grain boundaries and create avalanching Schottky junctions.



(a) (b)

Fig. 5. Barium titanate crystal structure, defects, and oxygen vacancy migration

Reduced Capacitance with Applied DC Voltage. This is not a failure in the sense that an initial parameter suffers degradation under stress over time, BUT it is a limiting factor that often sets the WVDC value in Class II dielectric capacitors, such as those used in the PPI broadband line. [Class II dielectrics can have much higher permittivities than their Class I counterparts, but exhibit increased temperature sensitivity, applied voltage sensitivity, aging, and microphonics.] The parameter involved here has the acronym VCC, the Voltage Coefficient of Capacitance. **Fig. 6** shows the decrease of capacitance with applied voltage for a typical PPI 0202BB104 broadband capacitor.

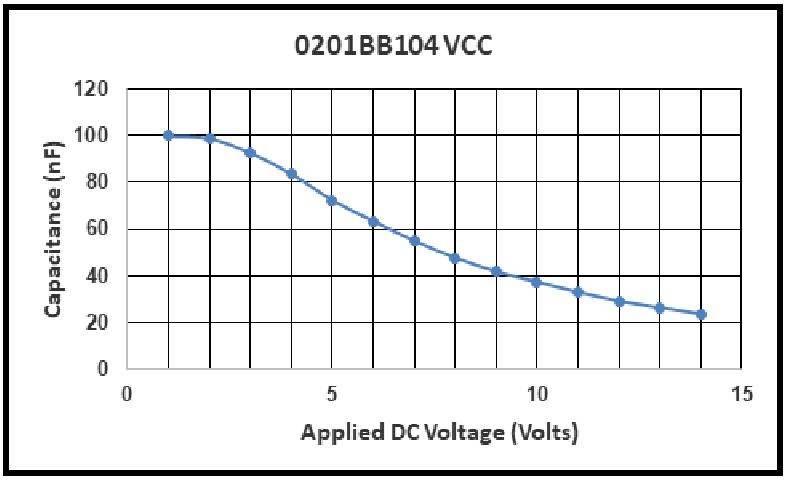


Fig. 6 Capacitance versus applied DC voltage for a typical PPI 0201BB104

For bypass and coupling applications, manufacturers would like to have both a WVDC and capacitance as high as possible. But while the limit on the former is reliability (failure rate), the limit on the latter is that the capacitive reactance must be sufficiently low (capacitance sufficiently high) to achieve good bypassing or coupling at user frequencies. For thin-layer BME Class II capacitors, the WVDC is often limited by the minimum capacitance rather than the reliability.

Thus, we may add yet another modification to our possible WVDC definition: **WVDC is the lower of: the applied DC voltage at which a specified maximum percentage of parts are expected to fail after a given operating time at a particular temperature and with a specified confidence level -- OR -- the applied DC voltage above which the capacitance drops below a certain value.**

RF Voltage Failures. When an RF voltage is applied, the situation, compared to DC voltage application, becomes even more complicated. Diagrams from some vendors suggest that no ***additional*** Life parameter degradation will occur as long as the peak RF voltage does not exceed the WVDC – but this is optimistic and really applies only to low frequencies. We do know, for example, that the RF voltage ***breakdown*** level is a function of frequency and, as frequency varies, may shift from external to internal. Further, it may depend on heating, which in turn depends on current through the part, on whether the applied voltage is pulsed or CW, and on the thermal conductivity of the ceramic-electrode structure.

And so now – finally -- with the preceding basic background and appreciation for the reader's patience -- we can commence with the main subject of this application note ….

Section III: Failures and Degradation Resulting From Applied Current

There are typically two basic limitations considered in the determination of MLCC current handling: (1) a current resulting in a peak voltage that exceeds the WVDC, and (2) a current resulting in a capacitor temperature that results in a particular probability of failure within a specific time. Now, it is possible that current can have additional limitations, such as creation of electromechanical stresses or electromigration – but these will not be covered herein.

<u>Current, I, is limited because of working voltage, WVDC</u>.

The implication here is that the "safe" peaks of a resulting sinusoidal voltage must not exceed the WVDC, although, as pointed out in the section on RF voltage failures, this may well not be a legitimate limiting criterion. In any event, if I_P is the peak value of the current (1.414 x the rms value), then – in the simplest approach -- the limiting condition for sinusoidal waveforms is expressed as

$$I_{MAX,RMS} \times 1.414 \times \frac{1}{2\pi f C} = WVDC \quad (9)$$

where f = frequency,
C = capacitance value

It is important to note here that the MLCC's impedance is assumed to be

$$Z_C - \frac{1}{2\pi f C} \quad (9a)$$

which doesn't consider the device's series inductance (nor the equivalent series resistance). For example, MLCCs are often operated at frequencies above series resonance, where their net impedance is inductive, not capacitive -- and not given by (9a), but rather by

$$Z_C = ESR + j\left(2\pi f L - \left(\frac{1}{2\pi f C}\right)\right) \quad (9b)$$

– with the concomitant result that (9) also does not apply. Note that at series resonance the net reactance is zero, a low voltage is developed across the capacitor, and so voltage-limited current handling will be much higher than (9). But above series resonance, when $2\pi f L > \frac{1}{2\pi f C}$, (9) can significantly <u>over</u>-estimate $I_{MAX.}$

We nevertheless ignore the above, since virtually all MLCC vendors do in specifying "voltage-limited current handling," and offer the relationship that guides this simplified dependency:

$$I_{MAX,\ RMS} = 1.414 \times \pi f C \times WVDC \quad (10)$$

Equation (10) indicates a linearly rising current capacity with frequency. From the discussion in the sections on RF voltage failures and failure rates in general, however, we realize that, even at frequencies where this is applicable, this is a very loose limit, with lots of caveats. For example, if we are willing to accept a higher failure rate, or one with different failure criteria, we can increase the WVDC and hence the current handling.

It should also not be forgotten that, in many applications (e.g., when one terminal of a coupling capacitor is connected to a transistor), there is both a DC (≡ DC_{BIAS}) and an AC voltage on the MLCC, so the current should be such that the AC peaks + DC_{BIAS} is less than the WVDC. I.e.,

$$I_{MAX,\ RMS} = 1.414 \times \pi f C \times \left(WVDC - DC_{BIAS}\right) \qquad (11)$$

<u>Current, I, is limited because of heating (capacitor temperature).</u>

Again, the assumption here is that the only effect of current is on the capacitor temperature and, further, that a thermal rise above ambient resulting from power dissipation inside the capacitor has the same effect as a corresponding ambient temperature increase.

Heat transfer is accomplished through three mechanisms: radiation, convection, and conduction. Let us initially assume the first two are negligible; then **Fig. 8** shows the temperature distribution in an MLCC under a specific set of conditions – steady-state, heat generated (dissipated) uniformly in its volume, and one-dimensional heat flow (conduction significant in one dimension only and negligible in the other two dimensions).

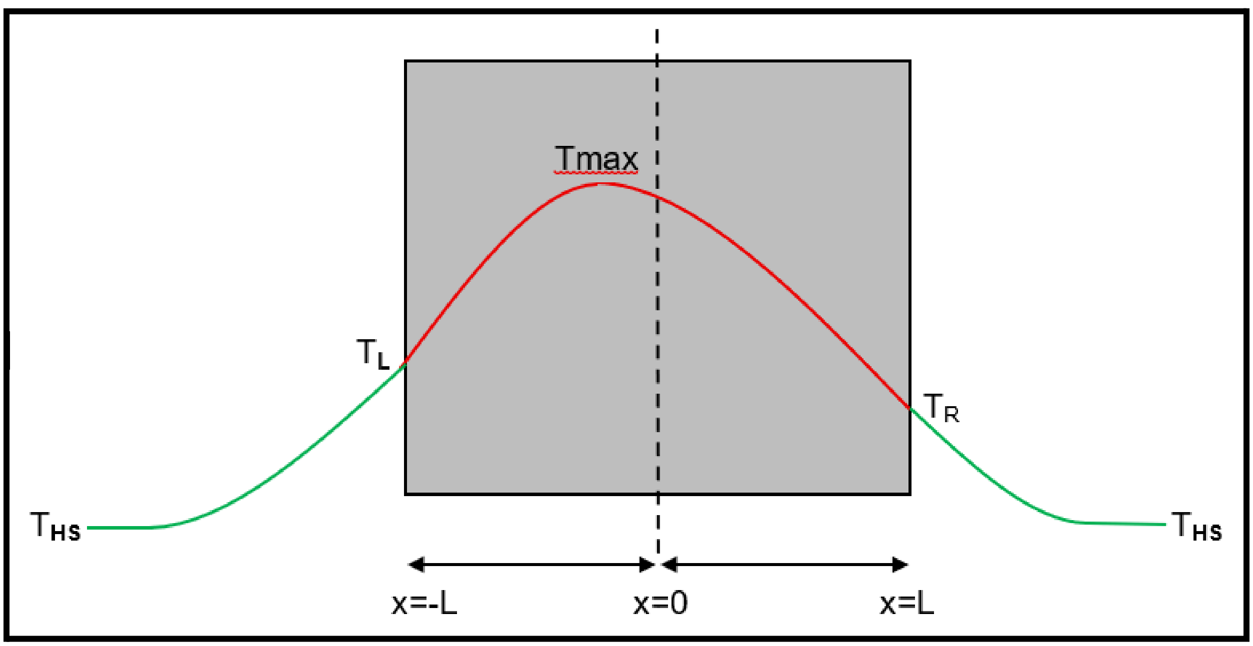


Fig. 8 Steady-state heat flow in an MLCC (no convection or radiation), heat assumed uniformly generated within capacitor volume and heat flow one-dimensional.

Clearly, MLCC construction, value and series differences, and specific cooling arrangements can make the one-dimensional approximation quite crude in a number of cases, but it nevertheless is a good starting point for understanding and characterizing thermal behavior.

Before proceeding, it is worth reviewing an analogue between thermal and electrical quantities. Consider the distributed electrical circuit in **Fig. 9**, where R is the resistance per unit length, and C is the capacitance per unit length.

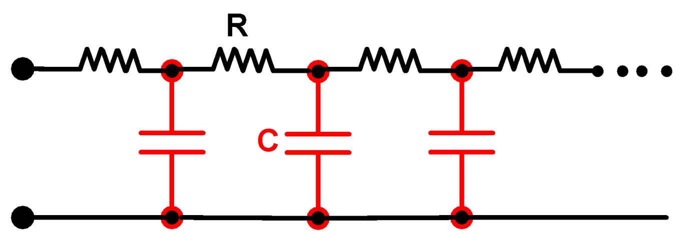


Fig. 9 Distributed R-C electrical circuit with thermal analogue

The differential equation describing the variation of voltage, V, with time, t, at any position, z, is:

$$\frac{\partial V}{\partial t} = \frac{1}{RC}\frac{\partial^2 V}{\partial z^2} \tag{12}$$

Since the Fourier one-dimensional heat-flow equation describing the variation of temperature, θ, with time, t, at any position, x, is

$$\frac{\partial \theta}{\partial t} = \frac{k}{\rho s}\frac{\partial^2 \theta}{\partial x^2} \tag{13}$$

Where k = *thermal conductivity*
ρ = density
s = specific heat

we have the following analogous quantities:

- **Temperature (θ) □ Voltage (V)**
- **Thermal Resistivity (1/k) □ Electrical Resistance per unit length (R)**
- **Thermal Capacitance (**ρs**) Electrical Capacitance per unit length (C)**

Thermal resistance, R_{TH}, is then given by the expression

$$R_{TH} = \frac{l}{kA} = \frac{\Delta\theta}{H} \tag{14}$$

where l = length of thermal conductor
A = cross-sectional area of thermal conductor
Δθ = temperature difference (^{0}C)

H = heat (Watts)

The corresponding electrical equation is then

$$R_{Elec} = \frac{\Delta V}{I} \tag{15}$$

where, current, I, and heat, H, are also analogues. (Note, this can be a bit confusing, since the electrical power is given by I^2R – all electrical quantities -- whereas the analogue of the thermal power, H, is I.)
Referring to **Fig. 8**, we may now consider three conditions of operation and their effect on current handling:

- **a) Steady-state operation, $T_R = T_L$**
- **b) Steady-state operation, $T_R \neq T_L$**
- **c) Pulsed operation**

In **Appendix 1**, the temperature distribution is derived for conditions a) and b) with a device having the following parameters (see **Fig. 8**) and typical units:

- Total length, l = 2L (m) in the x-direction (edges at x = ±L)
- Thermal conductivity = k ($\frac{W}{m\,°C}$), assumed herein independent of temperature
- Uniform volumetric heat generation rate = $\dot{e}_{gen}$ ($\frac{W}{m^3}$)

$$T(x) = \frac{T_R+T_L}{2} + \frac{T_R-T_L}{2L}x + \frac{\dot{e}_{gen}}{2k}(L^2 - x^2) \tag{A1-5}$$

The maximum temperature occurs at

$$x = \frac{(T_R-T_L)}{2L}\frac{k}{\dot{e}_{gen}} \tag{A1-8}$$

And is given by

$$T_{MAX} = \frac{T_R+T_L}{2} + \frac{(T_R-T_L)^2}{4L^2}\frac{k}{2\dot{e}_{gen}} + \frac{\dot{e}_{gen}}{2k}L^2 \tag{A1-9B}$$

Thus, for condition a), T_{MAX} is at the center, and is

$$T_{MAX} = T_L + \frac{\dot{e}_{gen}}{2k}L^2 \tag{16}$$

Observing that $\dot{e}_{gen} = \frac{W}{2LA}$ (since the total capacitor length over which power, W, is dissipated = 2L, and total capacitor volume is therefore $2LA$),

$$\frac{\dot{e}_{gen}}{2k}L^2 = \frac{W}{(2LA)2k}L^2 = \frac{W}{2}\frac{L}{2kA} \tag{17}$$

Letting $T_{MAX} - T_L = \Delta\theta$, we have

$$\Delta\theta = \frac{W}{2}\frac{L}{2kA} \tag{18}$$

<u>CASE a): $T_R = T_L$</u>

By (14) herein, the thermal resistance is given by

$$R_{TH} = \frac{L}{2kA} \tag{19}$$

And the heat flowing through R_{TH} is given by $H = \frac{W}{2}R_{TH}$.

In the steady state, the thermal equivalent circuit of a mounted MLCC with equal terminal temperatures is shown in **Fig. 10**, along with the relationships that govern the current that results in a given maximum capacitor temperature. Note that the power dissipated in the capacitor, W, is given by

$$W = I^2 ESR \tag{20}$$

where ESR = the **<u>E</u>**quivalent **<u>S</u>**eries **<u>R</u>**esistance of the capacitor

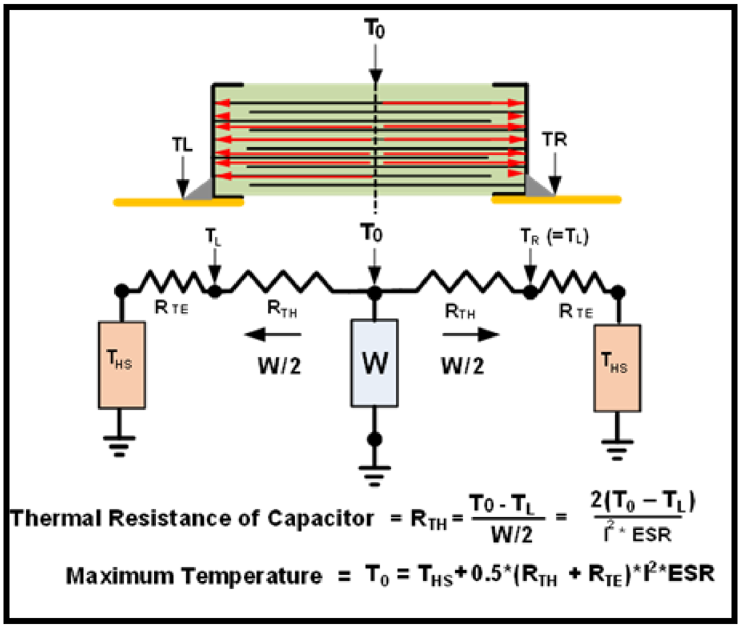


Fig. 10 Heat flow and thermal-electrical relationships in an MLCC with thermally symmetric boundary conditions

And thus, if T_0 is some maximum temperature, T_{MAX}, at which Life testing and specification is performed, then the corresponding maximum current is

$$I_{max} = \sqrt{\frac{T_0 - T_{HS}}{ESR*0.5(R_{TH} + R_{TE})}} \tag{20}$$

Note that R_{TE} is the thermal resistance from each capacitor termination to a heat sink at constant temperature T_{HS}.

Case b): $T_R \neq T_L$

For this case, the electric circuit-thermal analogue becomes that shown in **Fig.11**.

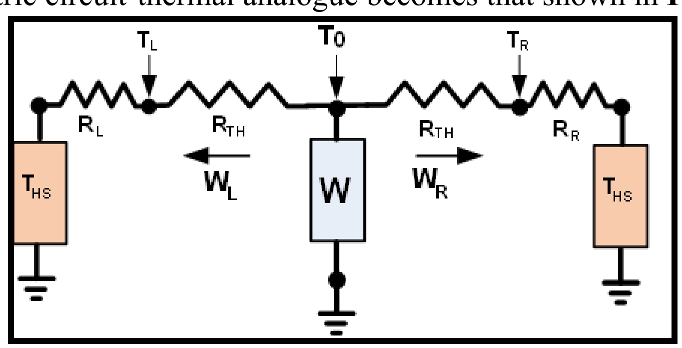


Fig. 11 Heat flow and thermal-electrical relationships in an MLCC with thermally asymmetric boundary conditions

Appendix B uses **Fig. 11** to derive expressions for these quantities in terms of the total heat dissipation, W, in the capacitor; the capacitor's thermal resistance R_{TH}; and each of the external thermal resistances, R_L and R_R, to a heat sink maintained at temperature T_{HS}. Results are as follows:

$$T_{MAX} = \frac{T_R+T_L}{2} + \frac{W}{2}R_{TH} + \left(\frac{T_R-T_L}{4}\right)^2 \frac{1}{\frac{W}{2}R_{TH}} \quad \text{(A2-7)}$$

where T_L and T_R are given, respectively, by (A2-3) and (A2-4):

$$T_L = T_{HS} + W_L R_L = T_{HS} + MW \quad \text{(A2-3)}$$

$$\text{where } M = R_L \frac{R_{TH}+R_R}{R_R+R_L+2R_{TH}} \quad \text{(A2-3a)}$$

And,

$$T_R = T_{HS} + W_L R_R = T_{HS} + NW \quad \text{(A2-4)}$$

$$\text{where } N = R_R \frac{R_{TH}+R_L}{R_R+R_L+2R_{TH}} \quad \text{(A2-4a)}$$

Note that if $R_R = R_L$,

$$T_L = T_R = T_{HS} + \frac{R_L W}{2} \quad \text{(A2-5)}$$

which is what one would expect from the **Fig. 10** circuit analogue.

Substituting (A2-3), and (A2-4) into (A2-7) then yields

$$T_{MAX} = T_{HS} + I_{MAX}^2 ESR\left[\frac{M+N+R_{TH}}{2} + \left(\frac{M-N}{2}\right)^2 \frac{1}{2R_{TH}}\right] \quad \text{(A2-14)}$$

And, finally, solving for I_{MAX} results in,

$$I_{MAX} = \sqrt{\frac{T_{MAX}-T_{HS}}{ESR\left[\frac{M+N+R_{TH}}{2} + \left(\frac{M-N}{2}\right)^2 \frac{1}{2R_{TH}}\right]}} \quad \text{(A2-15)}$$

Eq. (A2-15) is thus the (considerably more complicated) counterpart, for unequal terminal temperatures, to (20), the equal-terminal-temperature case.

Summarizing, finally: If we know or can determine the ESR, R_{TH}, R_R, R_L, and T_{HS} of a given configuration, we can express the maximum allowable current as a function of the maximum capacitor temperature.

Case c): Pulsed Operation

Because of the many variables and possibilities involving pulsed operation, we'll consider herein only the simplest case of equal termination temperatures. We can then think of the Fig. 10

equivalent analogue circuit re-drawn with the left and right branches in parallel, so that the net thermal resistance from the center at temperature $T_0 (= T_{Max})$ T_0 (= T_{MAX}) to the boundary temperatures $T_L (= T_R)$ is $\frac{R_{TH}}{2}$. From (19), this is given by

$$\frac{R_{TH}}{2} = \frac{L}{4kA} \tag{21}$$

We can now imagine the thermal capacitance of the MLCC in shunt with its thermal resistance to the boundary temperature to yield the circuit in **Fig. 12**.

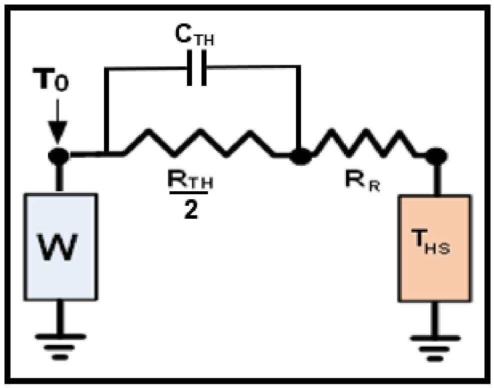


Fig. 12 Transient R-C Analogue for pulsed heating

The thermal capacitance is given by

$$C_{TH} = \rho sA(2L) \tag{22}$$

where the symbol definitions are given under (13). Thus, the thermal time constant is given by

$$\tau = \frac{R_{TH}C_{TH}}{2} = \frac{L}{4kA}\rho sA(2L) = \frac{\rho sL^2}{2k} \tag{23}$$

For a step heat input, W(t) = W_0, and initial T(0) = T_i the maximum temperature evolves as

$$T(0, t) = T_i + W_0\frac{R_{TH}}{2}(1 - e^{\frac{t}{\tau}}) \tag{24}$$

For a pulse heat input, one can convolve W(t) with the impulse response of the RC network, to derive the overall response.

BUT, it is important to recognize that the above analysis is for the thermal analogue electrical circuit, not the electrical circuit itself. The latter has its own, separate response to an electrical pulse – as distinguished from a thermal pulse -- determined by the MLCC's electrical capacitance, inductance, and ESR. It is the square of the current resulting from the electrical pulse multiplied by the ESR that determines the W(t) waveform that must be convolved with the impulse response of the thermal analogue circuit to determine $T(0, t)$.

Frequency Dependence of Maximum Current

The frequency dependence of thermally-limited I_{MAX} is related to that of the ESR, with MLCCs exhibiting a typical characteristic as shown in **Fig. 13**.

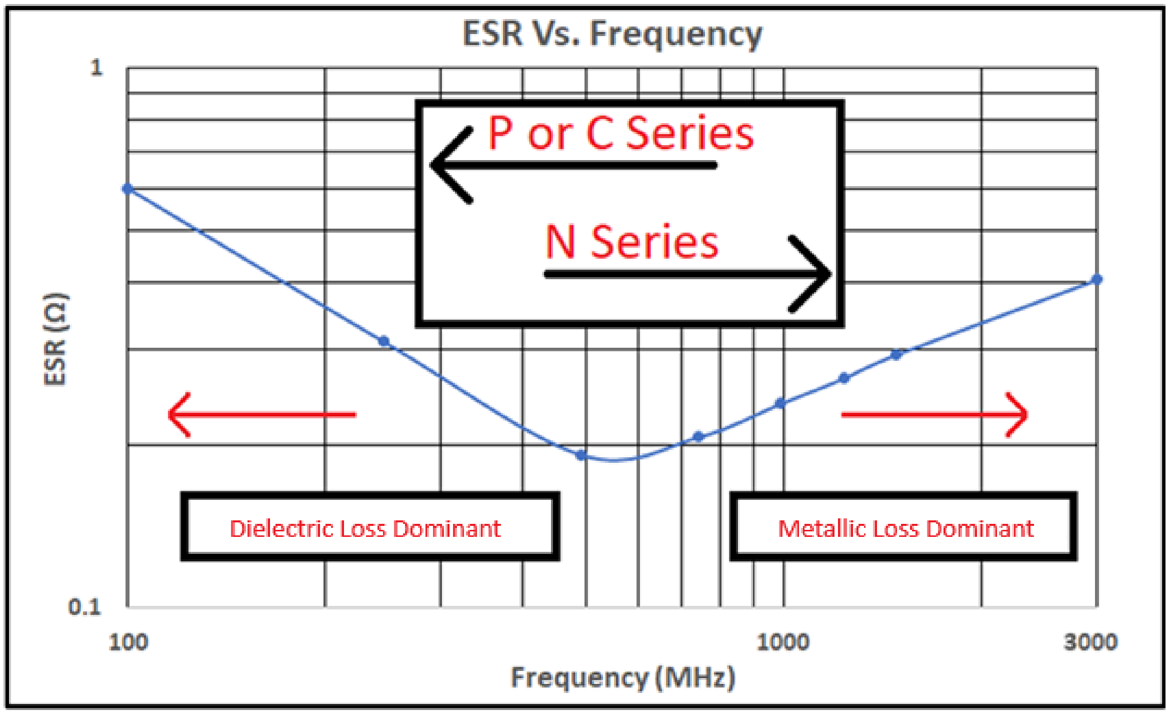


Fig. 13 Typical ESR dependence on frequency

Thus, combining voltage-limited behavior with thermally-limited behavior can lead to maximum current variation with characteristics shown in **Fig. 14**.

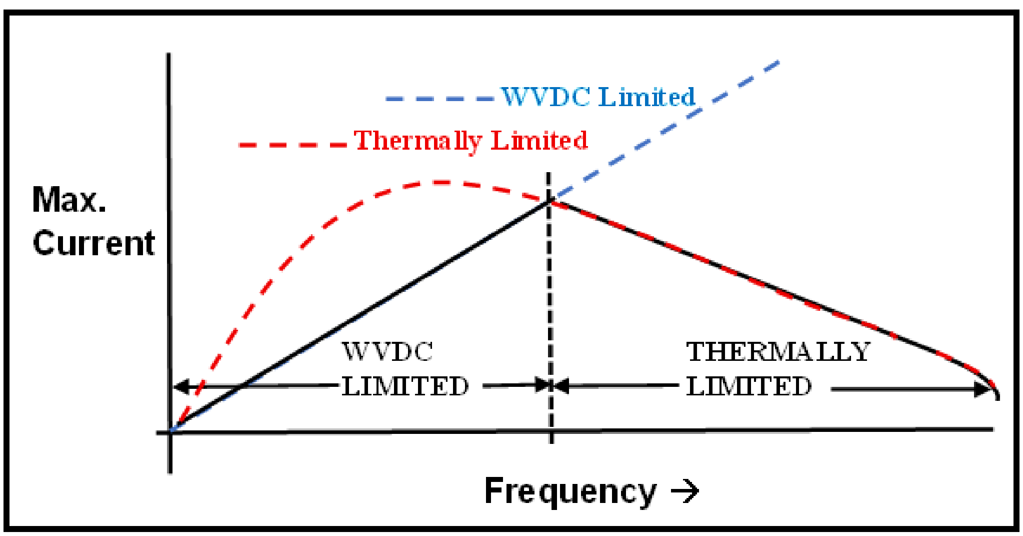


Fig. 14 Possible maximum current variation with frequency

But **Fig. 14** actually simplifies the possibilities, since, as noted, it assumes the working voltage is constrained by the DC limit, rather than any RF limits, and does not consider the capacitor's inductance and operation at frequencies above series resonance. (See the discussion under Eq. 9 herein.)

Section IV: Obstacles to Specifying a Maximum Current Rating

Definition. Because of the many factors already noted -- e.g. operating frequency, presence or absence of DC voltage across the capacitor, thermal environment, acceptable degradation of capacitance, DF, and IR over a given time period, etcetera – it is difficult, if not impossible to specify a single-number maximum current rating for an MLCC. Consider one such attempt by a few vendors to define the thermally-limited current as "that current that creates a 40 ^{0}C rise in the capacitor temperature." But from the Section I discussion on Reliability, we recognize that a 40 ^{0}C rise above a terminal temperature of 65 ^{0}C has a vastly different effect on Life compared to that same rise above a terminal temperature of 90 ^{0}C.

In light of the above, we can propose the following – admittedly, but purposely, somewhat vague -- definition of "Current Handling," the rationale being that non-specificity is better than incorrectness. **"The maximum allowable RF current through an MLCC is determined by two fundamental constraints: (1) The peaks of the resulting RF voltage shall not exceed the WVDC rating of the capacitor minus any DC bias voltage applied; and (2) The peak temperature of any point on the capacitor surface shall not exceed the temperature at which the MLCC was qualified to have a specified reliability."**

Parameter Measurement and Specification.

Apart from the issues already noted, simply measuring two of the basic cited MLCC parameters – ESR and R_{TH} – is often not straightforward.

ESR can be measured accurately by a coaxial resonator setup, but the standard instrument for performing this, the Boonton 34A coaxial resonant line, is (a) no longer commercially available, (b) can make measurements only at discrete frequencies that depend on capacitance value, (c) cannot accommodate physically large (e.g., a PPI 7676C or 1313C) capacitors; and (d) has various high-frequency limitations (e.g., higher coaxial modes) and low-frequency limitations (e.g., the so-called "shunt mode" for measuring at low-frequencies can accommodate only leaded devices.)

While some vendors (including PPI) have built their own, longer resonators to make measurements at lower frequencies, even these are generally limited to greater than a few MHz. (Accuracy depends on the resonator Q being much greater than the capacitor Q, and this is not the case for low frequencies and high-Q capacitors.) Other vendors use alternative instruments, e.g. Impedance Analyzers, to measure ESRs at low frequencies, but these have been found to have major inaccuracies when applied to high-Q MLCCs.

The measurement of thermal resistance is suggested by **Fig. 8 and Fig. 10**; it requires that the capacitor under test dissipate heat sufficient to raise the temperature at its center (T0) above that at its terminations by an amount that can be accurately measured by some instrument. Standard IR cameras often have issues with resolution (for physically small MLCCs), color compensation, and interference with the RF circuit because of required proximity to the devices. (PPI uses a contact thermal probe device to largely overcome these limitations.)

Summary and Conclusions.

Current handling, i.e., the specification of a maximum current capability for an MLCC, has a number of dependencies that make it a difficult and subtle metric to specify. In its most elementary form, it seeks to place maximum values on the current that causes any reduction in reliability, i.e., Life, beyond that predicted by the part's specification. The latter typically requires a mean survival time – where survival is defined as a minimum specified degradation in certain parameters, e.g., capacitance value, insulation resistance, and dissipation factor -- when a DC voltage is applied at a certain maximum temperature. In actual use, however, uncertainties arise when RF voltages are applied, since these are not tested for in the qualifying specifications, involve different physics within the MLCC structure, and create a temperature rise beyond that of the environment.

A simplified approach to specifying a maximum current involves calculating the value that does not produce a peak voltage across the MLCC in excess of the WVDC minus any DC bias voltage, or a surface temperature in excess of that for which a specified reliability has been measured/calculated. But both conditions are functions of the operating frequency, since:

- The voltage resulting from an RF current depends on the RF impedance – which may well differ from the simple $1/2\pi fC$, and
- The heating (temperature) depends on the ESR, which varies with frequency.

Accurate measurements of thermal resistance and ESR pose additional issues, as does current limits under pulsed operation, which involves not only the pulse parameters but the MLCC thermal capacitance, in addition to thermal resistance.

In summary, we've attempted to provide a basic theoretical background for understanding the factors involved in specifying maximum current handling for MLCCs, with the take-away messages of: Be conservative and recognize the complexities, and be aware of vendors' assumptions underlying "typical" data, as well as measurement accuracy limitations.

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Appendix 1 – Steady State Heat Flow in an MLCC

Herein, we approximate the heat flow in an MLCC: We assume it to be a solid with a uniform rate of heat generation (dissipation) in its volume, one-dimensional heat flow – conduction significant in one dimension only and negligible in the other two dimensions -- and the following parameters (in typical units):

- Total length = 2L (m) in the x-direction (edges at x = ±L)
- Thermal conductivity = k (W/m*C) (assumed herein independent of temperature)
- Uniform volumetric heat generation rate = e'_{gen} (W/m³)

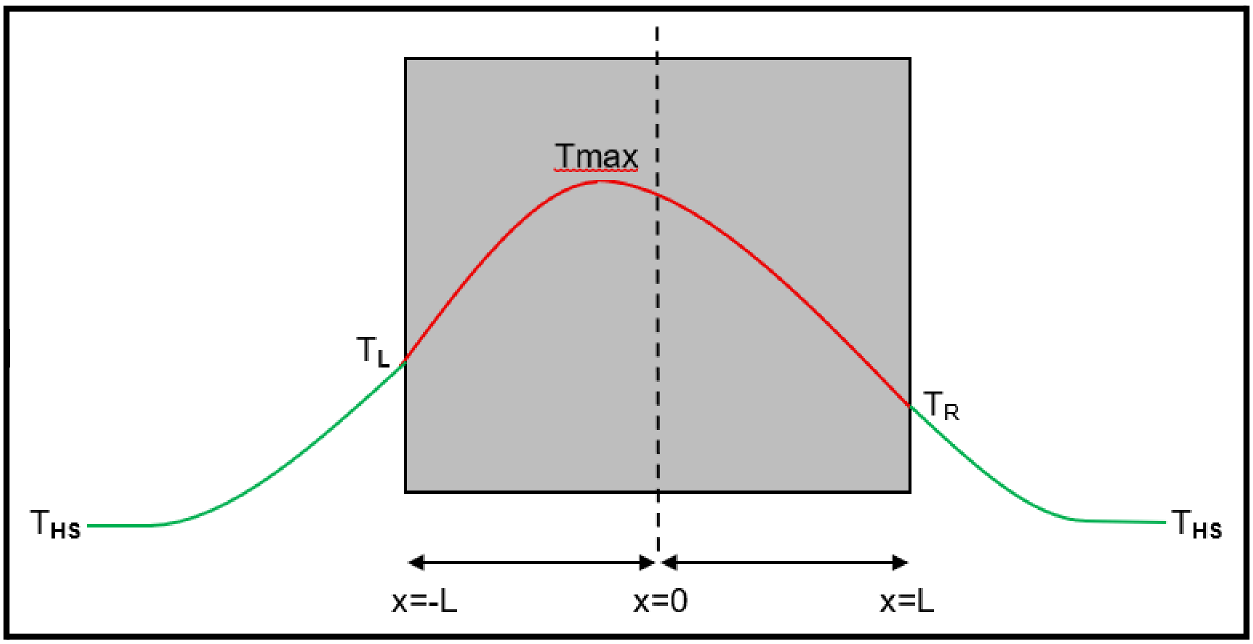

Fig. A1 One-Dimensional Approximation of heat flow in an MLCC

The 1-D steady heat equation (Poisson equation) with uniform volumetric heat generation is [14, eq.2-15]:

$$\frac{d^2T}{dx^2} = -\frac{\dot{e}_{gen}}{k} \qquad \text{(A1-1)}$$

If the left and right boundaries are held at different temperatures T_L (at x=-L) and T_R (at x=+L), we solve the 1-D steady heat equation with these boundary conditions.

Integrating d²T/dx² twice successively yields:

$$T(x) = -\frac{\dot{e}_{gen}}{2k}x^2 + c1x + c2 \qquad \text{(A1-2)}$$

Applying boundary conditions T(-L)=T_L and T(L)=T_R yields

$$c1 = \frac{T_R - T_L}{2L} \tag{A1-3}$$

$$c2 = \frac{T_R + T_L}{2} + \frac{\dot{e}_{gen}}{2k} L^2 \tag{A1-4}$$

Whence, the temperature profile is:

$$T(x) = \frac{T_R + T_L}{2} + \frac{T_R - T_L}{2L} x + \frac{\dot{e}_{gen}}{2k} (L^2 - x^2) \tag{A1-5}$$

The center temperature is:

$$T(0) = \frac{T_R + T_L}{2} + \frac{\dot{e}_{gen}}{2k} L^2 \tag{A1-6}$$

The maximum temperature is found by setting $\frac{dT(x)}{dx} = 0$

$$\frac{dT(x)}{dx} = \frac{T_R - T_L}{2L} + \frac{\dot{e}_{gen}}{2k}(-\ 2x) = 0 \tag{A1-7}$$

And the maximum temperature occurs at

$$x = \frac{(T_R - T_L)}{2L} \frac{k}{\dot{e}_{gen}} \tag{A1-8}$$

Thus, if $T_R = T_L$, the maximum temperature, T_{MAX}, occurs at $x = 0$; otherwise,

$$T_{MAX} = \frac{T_R + T_L}{2} + \frac{(T_R - T_L)}{2L} \frac{(T_R - T_L)}{2L} \frac{k}{\dot{e}_{gen}} + \frac{\dot{e}_{gen}}{2k} [L^2 - \left(\frac{(T_R - T_L)}{2L} \frac{k}{\dot{e}_{gen}} \right)^2] \tag{A1-9}$$

$$T_{MAX} = \frac{T_R + T_L}{2} + \frac{(T_R - T_L)^2}{4L^2} \frac{k}{\dot{e}_{gen}} + \frac{\dot{e}_{gen}}{2k} L^2 - \frac{\dot{e}_{gen}}{2k} \left(\frac{(T_R - T_L)}{2L} \frac{k}{\dot{e}_{gen}} \right)^2 \tag{A1-9A}$$

$$= \frac{T_R + T_L}{2} + \frac{(T_R - T_L)^2}{4L^2} \frac{k}{2\dot{e}_{gen}} + \frac{\dot{e}_{gen}}{2k} L^2 \tag{A1-9B}$$

$$= T(0) + \frac{(T_R - T_L)^2}{4L^2} \frac{k}{2\dot{e}_{gen}} \tag{A1-9C}$$

Appendix 2 – Steady State Heat Flow in an MLCC, Unequal Terminal Temperatures

Fig 10 of the main text shows the electric circuit analogue of heat-flow quantities when the capacitor terminals are at the same temperature. **Fig. A2-1** below indicates the modifications that arise when this is not the case.

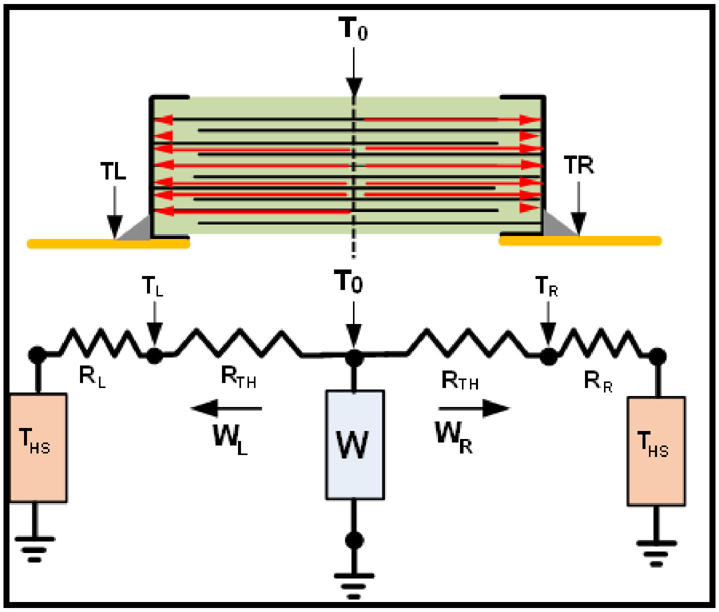

Fig. A2-1 Heat flow and thermal-electrical relationships in an MLCC with thermally asymmetric boundary conditions

Note that there are two ways to simulate (by electrical analogy) unequal terminal temperatures: (a) by simply placing voltage (analogue) sources of values T_L and T_R at the capacitor terminals, and (b) by using unequal external thermal resistances R_L and R_R to a heat sink (analogue voltage source). Method (b) was chosen herein, since it is closer to a real-world condition. For example, if one terminal of the capacitor is connected directly to ground, that ground point likely has a significantly lower thermal resistance to a heat sink than the other terminal that connects to a microstrip or CPL center conductor.

We proceed to express the respective temperatures T_L and T_R as functions of W, the total power dissipated in the capacitor.

Since the left and right circuit branches are in parallel,

$$W_L = W\frac{R_{TH}+R_R}{R_R+R_L+2R_{TH}} = FW \qquad \text{(A2-1)}$$

where W_L = heat (current analogue) in the left branch

$$F = \frac{R_{TH}+R_R}{R_R+R_L+2R_{TH}} \tag{A2-2}$$

Similarly,

$$W_R = W\frac{R_{TH}+R_L}{R_R+R_L+2R_{TH}} = GW \tag{A2-3}$$

where W_R = heat (current analogue) in the left branch

$$G = \frac{R_{TH}+R_L}{R_R+R_L+2R_{TH}} \tag{A2-4}$$

Whereupon,

$$T_L = T_{HS} + W_L R_L = T_{HS} + R_L FW = T_{HS} + MW \tag{A2-5}$$

where $M = R_L F$ (A2-6)

And,

$$T_R = T_{HS} + W_L R_R = T_{HS} + R_R GW = T_{HS} + NW \tag{A2-7}$$

where

$$N = R_R G \tag{A2-8}$$

Note that if $R_R = R_L$,

$$T_L = T_R = T_{HS} + \frac{R_L W}{2} \tag{A2-9}$$

Using the expression for T_{MAX} from A1-9,

$$T_{MAX} = \frac{T_R+T_L}{2} + \frac{(T_R-T_L)^2}{4L^2}\frac{k}{2\dot{e}_{gen}} + \frac{\dot{e}_{gen}}{2k}L^2 \tag{A1-9B}$$

and recalling the expression for $\dot{e}_{gen}$ noted under (16) in the main text,

$$\dot{e}_{gen} = \frac{W}{2LA} \tag{A2-10}$$

T_{MAX} can also be expressed as

$$T_{MAX} = \frac{T_R + T_L}{2} + \frac{W}{2}R_{TH} + \left(\frac{T_R - T_L}{4}\right)^2 \frac{1}{\frac{W}{2}R_{TH}} \quad \text{(A2-11)}$$

Substituting T_L and T_R, respectively, from (A2-5) and (A2-7) yields

$$T_{MAX} = T_{HS} + \frac{M+N}{2}W + \frac{W}{2}\left[R_{TH} + \left(\frac{M-N}{2}\right)^2 \frac{1}{R_{TH}}\right] \quad \text{(A2-12)}$$

And, simplifying,

$$T_{MAX} = T_{HS} + W\left[\frac{M+N+R_{TH}}{2} + \left(\frac{M-N}{2}\right)^2 \frac{1}{2R_{TH}}\right] \quad \text{(A2-13)}$$

Since the power dissipated in the capacitor, W, is given by (20) of the main text as

$$W = I^2 ESR \quad (20)$$

where ESR = the **E**quivalent **S**eries **R**esistance of the capacitor

the relation between T_{MAX} and I_{MAX} is

$$T_{MAX} = T_{HS} + I_{MAX}^2 ESR\left[\frac{M+N+R_{TH}}{2} + \left(\frac{M-N}{2}\right)^2 \frac{1}{2R_{TH}}\right] \quad \text{(A2-14)}$$

And solving for I_{MAX} yields,

$$I_{MAX} = \sqrt{\frac{T_{MAX} - T_{HS}}{ESR\left[\frac{M+N+R_{TH}}{2} + \left(\frac{M-N}{2}\right)^2 \frac{1}{2R_{TH}}\right]}} \quad \text{(A2-15)}$$