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Component Aging Is Primary Hurdle In Design Of High-Temperature Power Converters

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Extreme environments such as oil drilling, deep sea exploration, and space applications present daunting power supply design challenges. Power converters used in these applications, especially in “down-hole” drilling, may be subject to temperatures in excess of 200°C, while also facing extreme pressure. Relatively, few electronic components are rated for such high-temperature operation, and even when they are, their useful operating life may only be a matter of hours.

In most cases, the culprit is aging, which is accelerated by temperature. If the activation energy of a material or a device is known, its aging rate can be calculated as a function of temperature using a version of the Arrhenius equation. Moreover, for a given period of time and temperature, the Arrhenius equation can be used to predict component tolerances.

Even if you haven’t applied this equation directly, you’re probably familiar with the rule of thumb derived from Arrhenius. For every 10°C reduction in temperature, component life doubles. Naturally, for every 10°C increase in temperature, component life is halved.

The Arrhenius effects on component aging can be observed with nearly all components—active and passive. Unfortunately, even components with high temperature ratings are subject to Arrhenius effects. Therefore, in selecting components for a power converter design, it’s critical that the designer consider both temperature ratings and component aging as a function of temperature. Just as important as the device’s specified temperature rating is the useful life of the component at high temperature—something that may not be specified by vendors even for high-temperature components. Also, keep in mind that other operating conditions such as applied voltage can accelerate aging as well.

In this article, we’ll discuss the impact of temperature on the aging of resistors and capacitors with an eye toward assessing the useful life of these components at high temperatures (200°C and beyond). We’ll also discuss component options for achieving longer component life in such severe operating environments.

Film Resistors: Are They Worth The Savings?

In the past, designers developing circuitry for space and other high-reliability applications used RNC90Y hermetic glass-sealed resistors with a bulk metal foil element. These resistors are known to exhibit very low aging and thus could achieve reasonable tolerances even at high temperatures. The modern day equivalent is produced by Vishay’s Precision group in many styles.

However, the bulk foil resistors are expensive. As a low-cost alternative, designers have been turning to thick-film and thin-film resistors. For example, there are thick-film and thin-film resistors qualified to MIL-PRF-55342 that promise good performance for space applications at prices that are considerably lower than bulk-foil resistors. But is the tradeoff in price worth it?

A recent article studied M55342 thick-film chip resistors that were specified as having tolerances as tight as 1% with aging on the order of 0.2% after 10,000 hours.[1] However, both the initial tolerance specification and the aging specification reflect performance at room temperature. A study was undertaken to determine aging rates as a function of temperature using a modified version of the Arrhenius equation.

The basic Arrhenius formula is:

$$k = Ae^{-\frac{E_A}{RT}}$$

where k is a rate constant, A is a frequency or pre-exponential factor, E_A is activation energy in J per mole, R is the universal gas constant (= 8,314 J/molK), and T is temperature in Kelvin (uppercase K). If quantities are changed from moles to molecular units, then E_A can be expressed in electron volts (eV) and R is replaced by Boltzmann’s constant, which is represented by another lower case k and is approximated as 8.62×10^{-5} eV/K.

To avoid confusion, between the two lower case k's, we'll replace the first k with Q(T). In addition, T can be expressed in terms of a temperature differential for two temperatures T_{TEST} and $T_{OPERATE}$, so that the Arrhenius equation becomes:

$$Q(T) = Ae^{-\frac{E_A}{kT}} = Ae^{\frac{E_A}{k}(\frac{1}{T_{TEST}}-\frac{1}{T_{OPERATE}})}$$

where T_{TEST} represents a reference temperature for which we may have some recorded data on resistor aging and $T_{OPERATE}$ represents a second temperature for which we would like to know the change in resistor aging versus T_{TEST}. Both T_{TEST} and $T_{OPERATE}$ are ambient temperatures.

Substituting the numerical approximation for Boltzmann's constant and expressing temperature in Celsius, the equation becomes:

$$Q(T) = Ae^{\frac{E_A}{8.62\times10^{-5}}(\frac{1}{(T_{TEST}+273)}-\frac{1}{(T_{OPERATE}+273)})}$$

Then, assuming that resistor aging is a log function, the above equation is modified to include the effects of time by replacing the A term with:

$$[(a\times\log(t))-b]\times c$$

where a, b, and c are constants, and t is time in hours. This yields the expanded form of the Arrhenius equation:

$$Aging(time,temp) = [(a\times\log(t))-b]\times c\times e^{\frac{E_A}{8.62\times10^{-5}}(\frac{1}{(T_{TEST}+273)}-\frac{1}{(T_{OPERATE}+273)})}.$$

where Aging(time, temp) represents the aging or the percentage change in the resistor's value that occurs after t hours of operation at $T_{OPERATE}$. Note that the expression shown above for Q(T) provides a multiplication factor for resistor aging at $T_{OPERATE}$ relative to T_{TEST}. However, in the expanded version of the Arrhenius equation, the term [(a x log (t))-b] x c represents resistor aging at $T_{TEST.}$ When these two expressions for aging are multiplied together in the expanded version of the Arrhenius equation, the end result represents the absolute aging of the resistor after t hours of operation at $T_{OPERATE}$. Or, put another way, the result for Aging (time, temp) is the resistor's absolute tolerance (expressed as a percentage) due to aging at the specified operating temperature.

Using the above formula, together with raw data on resistor aging at 70°C provided by the resistor vendor, we determined (through curve fitting techniques) the values of constants a, b, and c in the above equation. Knowledge of the activation energy, while it necessary to apply the above equation to predict aging for a given time and temperature, was not required to determine the values of a, b, and c. Then, using additional resistor aging data taken at two temperatures, we derived a value of activation energy. Similar techniques can be applied to assess the activation energy of other components to asses aging rates at high temperatures and determine what types of aging tolerances may be seen in the application.

One source, Electrocomponent Science and Technology 1980, Vol; 6, pp. 241-246,[2] provided the following data, showing that at 70°C a resistor changed 0.2% and at 95°C after 100 hours it changed 0.62%.

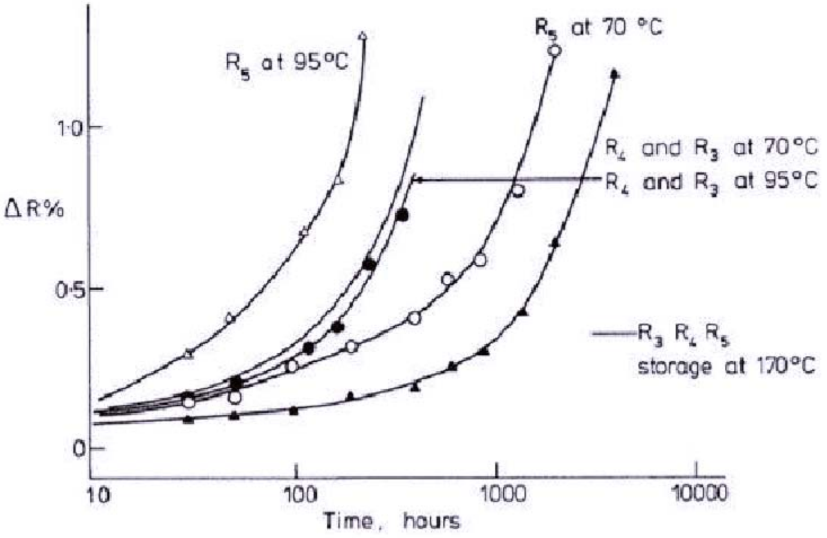

Fig.1. Response of 4.7-kΩ resistors over time to dissipation at ambient of 70°C and 95°C.
(Source: Electrocomponent Science and Technology 1980, Vol; 6, pp. 241-246.)

Fitting this data to the Arrhenius formula derived above, we obtain:

$$Aging(time,temp)=[(0.5\times\log(time))-0.675]\times 0.62\times e^{\frac{0.4924}{8.62\times10^{-5}}\left(\frac{1}{(273+70)}-\frac{1}{(273+temp)}\right)}$$

And we get the correct results at both 70°C and 95°C. We can then use this relationship to predict aging at 200°C after 100 hours

$$Aging(100,70)=0.201\%$$

$$Aging(100,95)=0.625\%$$

$$Aging(100,200)=19.594\%$$

so that we could see a potential tolerance band of 20% at 200°C after 100 hours.

The take away from this particular study of M55342 thick-film chip resistors was that as the ambient operating temperature increases above +70°C, the aging tolerance increases drastically, so much so that these devices could have a very limited useful life (a few hours?) at temperatures in the vicinity of 200°C. The study also determined the importance of pinning down a value of activation energy for the resistors being studied. Either this number must be supplied by the vendor, or the user must take their own aging measurements at elevated temperatures to derive an activation energy.

It should also be noted that activation energy is not necessarily a constant and may change from one manufacturing lot to another. Therefore, analysis may not yield a specific aging tolerance for a given time and temperature, but rather a statistical distribution of aging tolerances.

However, before embarking on your own studies of chip resistor aging consider some of the results obtained by other studies. For example, a paper presented at CARTS Europe 2005 analyzed the high-temperature stability of thin-film resistors at temperatures up to 210°C.[3] This paper also used an Arrhenius model to predict resistor tolerance as a function of time and temperature for resistors of a special high-temp stable thin-film formulation.

This study found that “Even after 1,000 hours at 210°C the change in value is satisfactorily below 1%.” However, when the same resistors were subject to time, temperature, and humidity, the study found that “temperatures up to 200°C are permissible for a limited time up to 100 hours.” So even for this specially formulated thin film, there was a significant impact of aging at 200°C. This paper also concluded that resistor aging continues even when the resistor is unpowered, and in fact can be worse when unpowered.

Another paper presented at CARTS Europe 2010 applies the Arrhenius model to different thin-film resistor systems further demonstrating its usefulness in predicting resistor aging as a function of temperature, though only looking at performance up to 175°C.[4]

Meanwhile, a paper presented in the Journal on IEEE Transactions on Components and Packaging Technologies studied the effects of high-temperature storage and thermal cycling in thick-film and wirewound resistors.[5] This study set out to assess the suitability of these resistor types "for distributed aircraft control systems in a 200°C–225°C operating environment."

With regard to thick-film resistors, this study found, "The thick film resistors [were] an acceptable choice for low power resistor needs at higher temperatures. The Heraeus–Cermalloy R900 pastes could be used to achieve the range of values from 100 Ω to 100 kΩ. The tests performed on these thick film pastes show that the resistors should be able to meet 5% tolerance requirements necessary for most applications in the high temperature range (175°C–250°C). Gold terminations are required to operate these resistors at these elevated temperatures."

Unfortunately, even a 5% tolerance could be problematic as illustrated by the following design example.

For film resistors (Mil-prf-55342), we calculated a resistance change of 20% after 100 hrs at 200°C or 2%/decade hour. Consider the case of a 5-V regulator with a 2.5-V reference. Assuming the reference shows no aging at all and each resistor in the voltage sensing divider changes 2.5% (one up and one down) the regulator might exceed the 5% allowed voltage tolerance of logic devices in either the low or high direction within 10 hours of operation! This makes the regulator incompatible with logic devices or only usable for a very short life circuit. Furthermore, since the reference drifts with time and temperature, the useful life of the regulator would be reduced still further.

Clearly, there are many contradictory studies, indicating that there are other influences on resistor tolerance besides aging, such as environmental conditions and manufacturing-related tolerances. One study cited above mentioned the effects of laquer, while another mentioned the impact of the metal used in the terminations. Then there's the impact of soldering the part to the board, electrical stress in the application, and other environmental conditions such as humidity and pressure, which may influence resistor tolerance.

In each application, the designer needs to carefully consider the possible tolerance range to determine whether precision devices such as bulk-foil resistors are necessary even though they are much more expensive than thick- or thin-film resistors.

Precision bulk-foil resistors are still being developed. Some recently released devices include Vishay's HTH, HTHA, and FRSH series, which are chip resistors designed for use in applications up to +240°C.[6] The vendor's datasheets for these resistors specify tolerances at this extreme temperature at 2000 hours of operation, as well as tolerances over other conditions.

Vishay's Yuval Hernik, explains how these components achieve tight tolerances in the intended applications. "The newly advanced structural design of the foil resistors for high-temperature projects employs a pre-planned stress compensation that never exceeds Hook's constant for the materials,“ says Hernik. "Therefore, the resistors maintain their molecular-level structural integrity and assure resistance stability throughout the load-life and application environments of the resistor—holding resistance change to less than 0.05 % throughout the planned life of the equipment also under extreme environment conditions such as high temperature."

The cost savings of using a thick- or thin-film resistor may easily be lost in the wake of expensive field failures. As we all know, the key to reliability is to keep devices cool and unfortunately, in extreme-temperature applications such as down-hole electronics, that is not always an option.

Capacitor Options Are Limited

Multilayer ceramic capacitors (MLCCs) and tantalum capacitors are seemingly candidates for high-temperature operation. For both chemistries, there are components available with operation rated up to 175°C or in the case of MLCCs up to 300°C.[7]

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With MLCCs, if you can stick with COG dielectric, aging will be minimal and performance at high temperatures will be acceptable. However, COG capacitors limit your capacitance range up to approximately 50 nF.[8] On the other hand, an X7R dielectric, which offers values up to about 33 µF, exhibits an aging rate of 2% per decade hour[7] and so is unlikely to yield acceptable performance at 200°C beyond a usable life of 10 hours or so.

For larger capacitance values, there are tantalum capacitors offering 175°C ratings and capacitance values up to about 150 µF.[9] However, there are reliability issues even with the 175°C-rated parts such as derating of the capacitor over temperature. For example, one 175°C-rated tantalum[9] derates maximum working voltage at 175°C to one third its nominal value. Moreover, this derating is accompanied by the qualifier "maximum 500 hours," which suggests that operating life would be further reduced at 200°C, assuming the part would operate there. There's a second disclaimer that notes "Details for this operating condition must be agreed upon between supplier and customer."

Another 175°C-rated tantalum series of surface-mount capacitors offers values up to 220 µF and voltage ratings to 50 Vdc.[10] The operating life for this capacitor series is specified at half voltage and 175°C, which results in decent performance specifications. However, with this particular series, the published ripple current ratings are close to zero at 125°C and are not even specified at 175°C. Also, note that this part's working voltage is derated 50% at 175°C. Morever, the vendor advises that the capacitors should be stored at temperatures below 40ºC, which (like the thin-film resistor study cited previously) tends to suggest that aging continues even when the device is unpowered.

The point here is not to single out any particular capacitor series, but rather to illustrate how even capacitors that are rated for high-temperature operation are typically not characterized adequately for operation at the rated temperature, and it is up to the user to analyze the probable performance of these devices at 200°C and under other extreme conditions. Again, it's sometimes possible, depending on the dielectric, to apply Arrhenius models to obtain estimates of device tolerances as was previously discussed with respect to resistors. There are various examples in the literature of the use of Arrhenius equations to assess capacitor aging over temperature, and so gauge device performance beyond the specified datasheet limits.[11,12]

Conclusion

This discussion of resistor and capacitor aging points to the importance of Arrhenius effects and other influences that can make component performance so unpredictable at extreme operating temperatures such as 200°C. In power supply applications, the lack of adequate component characterization over temperature by the vendor often places the burden of device characterization on the shoulders of the power system designer. In many cases, designers will need to choose between expensive precision components with aging rates (and other characteristics) that are known and less expensive components with higher aging rates, or aging rates that are poorly characterized. Designers will have to decide whether they spend more on the selected components, or invest more development effort and cost in the characterization of less expensive components. Given the lack of data, application-specific testing will be a necessity if limited-life components are to be identified and their performance quantified.

In high-volume applications, such engineering efforts may be amortized over millions of units. Meanwhile, in high-reliability, low- to medium-volume applications, the potential cost associated with field failures may negate any potential component savings. The actual operating temperatures expected in the application will weigh heavily in these decisions as there is a world of difference in component reliability even going from just 150°C operation to 200°C operation.

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About The Author

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For more on the design of power converters for high-temperature operation, see the How2Power Design Guide, select the Advanced Search option, go to Search by Design Guide Category, and select "Extreme Heat" in the Extreme Environments category.

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