# Predicting Drift in Foil Resistors

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**ABSTRACT**

The reliable functioning of electronic devices that incorporate high-precision resistors requires maintaining the specified precision over the full life of the device. As the precision and stability of foil resistors is expressed in parts per million, a precise prediction method of the resistors' behavior under different loads and time periods is required. Based on test data gathered over four decades of production and testing, an equation based on the Arrhenius rate law is derived for calculation of the standard deviation of the Gaussian distribution of resistance drifts. The mean value of the drifts' distribution is evaluated and allows the calculation of the maximum drift for any requested confidence level.

## INTRODUCTION

There is a growing demand from the market to increase the quality and reliability of precision resistors used in industrial, medical, military, and aerospace applications that require precision and stability over a long time. Representative applications include current sensing, signal amplifiers, and precise control systems. Precision and stability are especially important in self-guided systems, such as satellites or missiles that cannot be calibrated periodically.

Therefore, one of the challenges that design engineers are facing today is how to predict with high accuracy the reliability of resistors over time, after they have been mounted on circuit boards.

The resistor quality is defined in terms of initial precision (tolerance), stability with ambient temperature changes (reversible changes), and reliability in terms of drift in the resistor's ohmic value during its service life (irreversible changes). Certain applications today require tolerances down to 0.001 % and drifts as low as a few parts per million (ppm) over the resistor's service life.

Of all existing resistor manufacturing technologies, foil technology provides the best quality in all three aspects: precision, stability, and reliability (see the appendix for more information on TCR). Therefore, the need for an efficient and accurate method to predict the resistor's drift due to stresses imposed by a specific application is especially important for this technology.

The common method to predict irreversible changes in a resistor's ohmic value during its service life is based on load life tests and mathematical equations derived from the Arrhenius rate law. This law defines the speed of a single chemical reaction as a function of Kelvin temperature. In this paper we will use a similar equation, and will consider additional phenomena causing small drifts that cannot be neglected in discussions of precision resistors.

The load life test is performed by submitting resistors to their nominal rated power at an elevated ambient temperature for a period of at least 1000 h. In order to receive an accurate prediction of the drift, we will consider foil's homogenous heating due to changes in the ambient temperature, and the Joule effect—self heating of the resistor under load, causing a drift which occurs mainly at hot spots.

All of the above considerations and the extensive statistics collected on foil resistor behavior over a long period and under different conditions yield a method for predicting foil resistor behavior under various load conditions and service times. This method can help design engineers select foil resistors for various high-precision applications.

The equations derived from extensive testing permit the calculation of the standard deviation of drifts' distribution as a function of ambient temperature, electrical load, and service time. As the scattering of drifts exhibits a Gaussian distribution, the maximum drift deviation from the mean value for any requested confidence level can be calculated.

The mean value of the drift depends on the resistor's history up to and including its assembly in the electronic circuit and can vary between –30 ppm and +100 ppm. In case a more precise estimate is required, a method of accelerated testing is recommended.

Based on the mean and standard deviation the maximum value of the drift can be calculated for any combination of load, service time and the required confidence level.

## REVERSIBLE AND IRREVERSIBLE PHENOMENA ASSOCIATED WITH OHM'S LAW

According to ohm's law, E = R x I; the voltage drop across a resistive device is proportional to the current flowing through it, and the ohmic value of the device is assumed to be constant.

However different types of real life resistors show, during their useful life, different amounts of deviations, both reversible and irreversible, from their initial ohmic values.

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The possibility of prediction of resistance changes is especially important for electronic circuits requiring high-precision end of life tolerance better than 1 %.

The prevailing production technologies of precision resistors today are the thin film and, where even higher precision and stability are required—the foil resistors.

External constraints causing reversible changes of resistance are:

- Change of temperature within the resistor's rated temperature range—defined by the temperature coefficient of resistance (TCR)
- Electric field
- Magnetic induction
- Mechanical strain

With removal of these constrains, resistors revert, after a stabilization period, to their former ohmic values.

Irreversible change of resistance, or drift D, is quantified by the relative resistance change;

$$D = (R_t - R_0)/R_0$$

expressed in % or, in precision resistors, adjusted for ppm (parts per million).

$R_t$ is the ohmic value measured at time t and $R_0$ is the initial value, at time zero, both measured at the same temperature.

The mechanisms of drift with time and temperature are mainly due to:

- Physio-chemical reactions in the metals forming the resistive element and in the insulating materials
- Strain changes due to relaxation or creation of mechanical stresses in the resistive element

These mechanisms differ from resistor to resistor, and even more so between different resistor technologies. Thin film load life prediction methods use the Arrhenius equation to calculate the maximum predicted drift during load life. This equation assumes a single chemical reaction and does not take into account the different influences on the resistance value, such as the changing ambient temperature versus the self heating effect. The average temperature of the resistive element is calculated by adding the temperature rise due to self heating to the ambient temperature. However self heating also creates hot spots where the chemical reaction is accelerated, causing increased drifts.

## METHODS OF PREDICTING DRIFT IN FOIL RESISTORS

The prediction of the main drift in foil resistors is based on data from long term load life ttesting of resistors under different conditions of ambient temperature, and over shorter periods using accelerated testing of newly produced resistors.

For existing products the tests are performed according to rules set by standards of load life (or endurance) tests, which define the applied load, the ambient temperature, and the timing of periodical measurements.

Temperature rise due to load-induced self heating is added to the ambient temperature to obtain the average temperature of the resistive material.

Foil's temperature rise can be further influenced by heat flow from neighboring components—see N140401-801, par. 1.9.8—temperature rise for high packaging density.

Based on test results and on an Arrhenius equation, the drift's standard deviation ($D_{SD}$) can be calculated for any other set of parameters—such as time period and the resistor element's temperature.

The tests provide, for a given time t of exposure, coordinates of two points of a straight line y = ax + b, where x is the reciprocal of foil's absolute temperature and y is the natural logarithm of the drift.

The Arrhenius equation is:

$$\ln(SD) = a \times \frac{1}{T_k} + b \qquad (1)$$

The first point of this line, $SD_1$, drift after endurance test, is defined by selection, from the test data of foil resistors, of the relevant specifications: load life (endurance)—load P, ambient temperature $T_a$, duration t and the standard deviation of drift values, $D_{SD1}$ of the population.

The foil's average temperature $T_f$ is computed by adding the temperature rise due to the self heating, $T_s$, to the ambient $T_a$.

$T_s$ is calculated from the load and the thermal resistance, foil to ambient, $R_{th}$: $T_s = P \times R_{th}$

$$T_f = T_s + T_a \qquad (2)$$

In our case: t = 10 000 h, $T_{f1}$ = 425 K, and $SD_1$ = 100 ppm

The second point, $D_{SD2}$, of the straight line can be similarly defined from the shelf life test which resulted, after 10 000 h, in a 20 ppm drift's standard deviation.

The equation below, of a straight line through two points defined above, gives the natural logarithm of the standard deviation of drift $D_{SD}$ for 10 000 h of exposure as a function of the reciprocal of the foil's absolute temperature.

$$\ln(D_{SD}) = -2068.6/T_k + 9.4725 \qquad (3)$$

The equation is represented graphically in figures 1 and 2.

# Predicting Drift in Foil Resistors

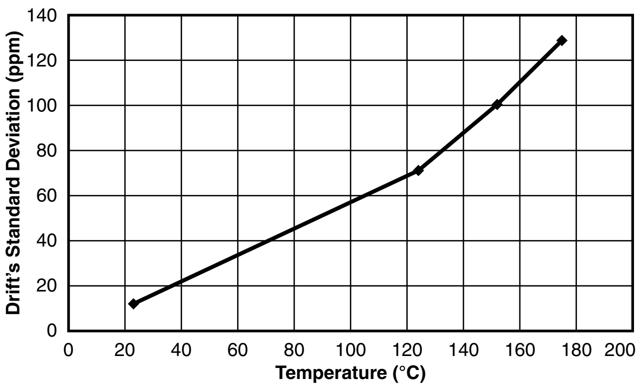


Fig. 1 - 10 000 h Drift's Standard Deviation as Function of Foil's Temperature

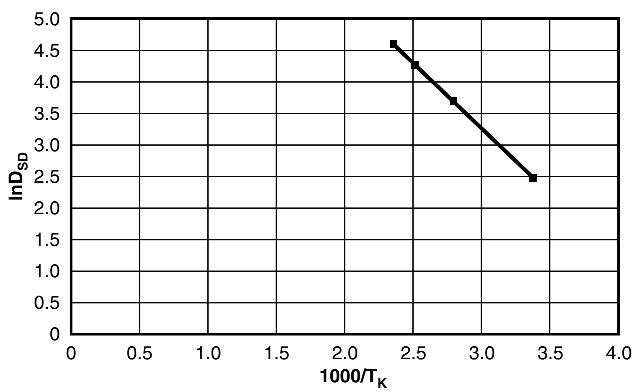


Fig. 2 - 10 000 h Drift's Standard Deviation as Function of the Reciprocal of Foil's Kelvin Temperature (Logarithmic Scale)

Figure 3 is an example of results obtained from a test involving a group of 96 foil resistors.

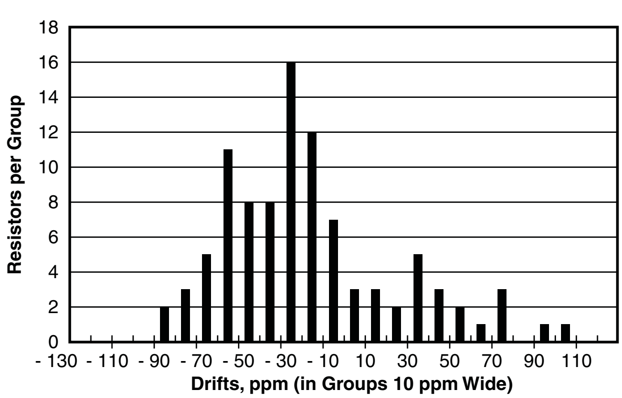


Fig. 3 - Histogram of Drifts for Endurance Testing of 96 Resistors, 10 kΩ, VFR Style S102C

The mean value of the distribution is relatively small and will be dealt with later.

Based on the $D_{SD}$, the maximum drift's deviation from the mean value

$$D_{max.} = n \times D_{SD} \tag{4}$$

for any confidence level CL can be calculated using a number n from table 1 or from a probability function for standard normal distribution, for confidence interval $-D_{max.}$ to $+D_{max.}$.

**Note**

Since the MS Excel function NORMINV refers to an interval minus infinity to plus $D_{max.}$ (as opposed to $-D_{max.}$ to $+D_{max.}$ in our case), the argument used for probability should include the "tail" between minus infinity and the $-D_{max.}$ value and therefore should be (0.5 + CL/2).

**TABLE 1 - CONFIDENCE LEVELS AND NUMBER N OF $D_{SD}$'S**

| Conf. Level, % | 68.3 | 90 | 95 | 95.4 | 99 | 99.73 |
|---|---|---|---|---|---|---|
| # of $D_{SD}$'s, n | 1 | 1.64 | 1.96 | 2 | 2.58 | 3 |

Using the most popular confidence level of 95% we reach, for 10 000 h of exposure of VFR's S102C style resistors, a maximum drift of 196 ppm for endurance at 0.3 W load and 125°C ambient temperature. The self heating effect raises the average foil's temperature by 0.3 x 90 = 27°C (90°C per W) the foil's temperature to:

$$273 + 125 + 27 = 425°K$$

Drift for any other time t (in h) of exposure, can be estimated by multiplying the 10 000 h drift value by a coefficient c—the cube root of the ratio t/10 000:

$$c = \sqrt[3]{0.0001t} \tag{5}$$

An important matter to note is that the combination of the change of ambient temperature and Joule effect heat rise to calculate the temperature of the resistive element is only applicable up to power levels marginally higher than the nominal rated power of the resistor. Due to the construction of resistors, at higher power levels, high current concentrations appear in certain areas of the resistor's pattern, causing "hot spots". These hot spots have a higher temperature than the average temperature of the resistive foil, and therefore the changes which cause resistance drifts are accelerated at these areas. This causes the overall resistance drift over time to be higher than it would be at the same overall temperature with a lower self heating/ambient temperature rise ratio. An example of this effect can be seen in figure.4. The calculated temperatures for the two loads of resistors in this graph are:

$$T_{1\,W} = 25\ °C + 1 \times 90 = 115\ °C$$

$$T_{1.5\,W} = 25\ °C + 1.5 \times 90 = 160\ °C$$

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So, while there is only a 45°C difference between the average temperatures of the two resistors, the hot spots caused by applying over two times the nominal power for an extended time period causes resistance drifts much higher than would be expected.

The table below compares the standard deviation of drift calculated using the equations 3 and 5 with the $D_{SD}$ obtained by testing: For the load of 1 W, which is 67 % above the nominal load at 70 °C ambient, the calculated and tested values are close (20 ppm and 17 ppm), while the test results for 1.5 W indicate that the equations cannot be applied to loads 2.5 times the rated load.

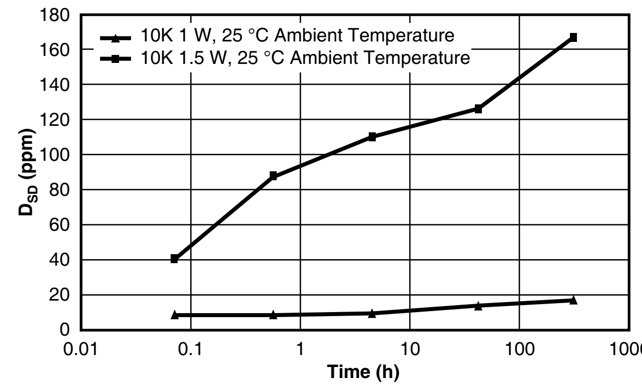


Fig. 4 - Standard Deviation of Drift over 13 Days for 10K VFR S102C Style Resistors at 25 °C at 1 W and 1.5 W. Nominal Power for this Style is 0.6 W at 70 °C.

**TABLE 2 - ACCELERATED TESTING RESULTS OF SD COMPARED WITH VALUES CALCULATED USING THE PREDICTION EQUATIONS**

| POWER APPLIED (W) | TEMPERATURE RISE (°K) | FOIL'S TEMPERATURE (°K) | TEST TIME (h) | $D_{SD}$ (ppm) | |
|---|---|---|---|---|---|
| | | | | CALCULATED | TESTED |
| 1 | 90 | 388 | 312 | 20 | 17.14 |
| 1.5 | 135 | 433 | 312 | 34 | 167 |

## BEHAVIOR OF THE MEAN VALUE OF DRIFT DISTRIBUTION

As mentioned in the introduction, the mean value of the distribution of drifts in load life tests at nominal power rating and ambient temperature (e.g. 0.3 W at 125 °C for the S102C style) changes between –30 ppm and +100 ppm.

When continuous load is applied, the mean value first becomes negative and after time becomes positive. The negative drift can be explained by getting rid of absorbed moisture, stress relaxation in the bonding cement and shrinkage of the cement. The influence of these factors depends on the resistor's history, shipping conditions, and changes when the resistors are assembled by the customer.

Some, but not all, of these phenomena can be reduced by "burn in" operations performed by the supplier in a way to fit a given application.

In case a more precise knowledge of the mean drift is required, it is recommended to perform an accelerated test on a sampled lot of resistors.

## PREDICTION OF DRIFT - EXAMPLE OF CALCULATION

### DATA

Load (W): 0.4
Thermal resistance, foil to ambient (°C/W): 100
Ambient temperature (°C): 70
Duration of load (h): 1250
Confidence level CL (%): 95

### CALCULATION

Foil temperature, per equation 2 (°K):
273 + (0.4 x 100) + 70 = 383
Per equation 3: $D_{SD}$ = 59 ppm for 10 000 h
For CL of 95 %, per table 1: n = 1.96
$D_{max.}$ = 59 x 1.96 = 116 ppm
For 1250 h per equation 5: c = $0.125^{1/3}$ = 0.5
C x $D_{max.}$ = 116 x 0.5 = 58 ppm
Minimum drift (mean = –30 ppm): –30 –58 = –88 ppm
Maximum drift (mean = 100 ppm): 100 + 58 = + 158 ppm

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## REMARKS

1. The Arrhenius' law is valid for a single mechanism causing the drift while the test results on which our equation is based refer to at least two mechanisms of irreversible drift. For instance, the shelf life testing of foil resistors (not hermetically sealed styles) indicate a seasonal fluctuation of about 20 ppm due to moisture absorption with a changing ambient humidity level. When load life is tested, the resistors are always at a temperature higher than the ambient, and therefore dry. But when the test results are extrapolated to applications causing drifts of a few tens of ppm, this moisture absorption related drift should be taken into account.
2. An additional mechanism concerns ohmic values below 100 Ω. The ohmic value of internal connections can change with time and temperature by a few milliohms—a drift equivalent to 10 ppm in a 100 Ω resistor and of 1000 ppm in a 1 Ω resistor. Very low-value foil resistors require special construction of their internal connections. For values below 0.5 Ω the "Metal Strip" style of resistors includes very robust internal connections and an option of a four terminal external connection.
3. The equations are based on test results for ohmic values close to the maximum resistance for the given style and therefore can be considered "worst case." The histogram showing test results from endurance test on a group of 96 10 kΩ resistors indicates a maximum drift of 120 ppm for a confidence level similar to the calculated worst case drift of 196 ppm.
4. Correction factors for drifts in lower values and thermal resistance data can be obtained from the Applications Engineering Department at: foil@vishaypg.com

## APPENDIX

### ZERO TCR OF FOIL RESISTORS

Ultimately, the TCR of the foil resistor is affected by two opposing physical phenomena, which depend both on the resistive element on its own, and its relationship to the substrate to which it is bonded.

Resistivity of the free foil changes directly with temperature. After bonding, the difference of the temperature coefficient of expansion (TCE) between the foil and the substrate will cause compression or expansion strains on the much thinner foil, directly affecting the resistance change with temperature (strain gage effect).

These two effects occur simultaneously on the resistor with temperature changes, and can be detrimental to the performance of the resistor. They can however, also be used to negate each other toward improving the overall temperature characteristics of the resistor.

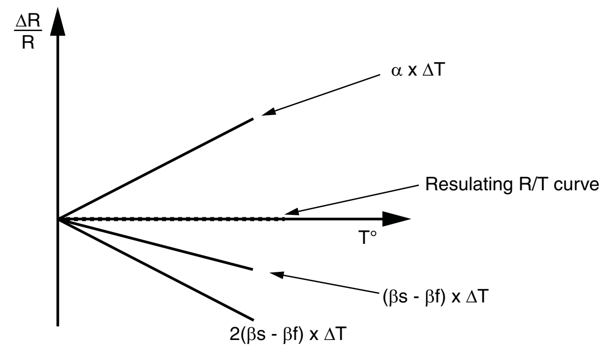


Fig. 5 - Resistance Change of the Free Foil with Change of Temperature. αΔT is Counteracted, after Bonding, by the Strain Gage Effect, 2(βs – βf)ΔT

Figure 5 illustrates how Bulk Metal Foil technology achieves its TCR by matching the change of resistance of the foil with temperature to the change of resistance of the foil due to strain.

$\alpha$ represents the TCR (temperature coefficient of resistance) of the resistive element (Nickel Chromium alloy) and is measured as $\alpha = \frac{\Delta R / R}{\Delta T}$ in ppm/°C.

$\Delta\beta$ represents the difference in expansion coefficients between the foil resistive element and the substrate – $\beta s$ and $\beta f$ for the substrate and the foil respectively, and is measured as $\Delta\beta = \langle \beta_s - \beta_f \rangle$ in ppm/°C.

Since the foil is much thinner than the substrate, it follows substrate's expansion resulting in a strain $\frac{\Delta L}{L} = \Delta T \times \Delta\beta$ and resistance change $\frac{\Delta R}{R} = \frac{\Delta L}{L} \times GF$

GF is the gage factor, which defines the ratio of resistance change to the strain causing it. For foil resistors GF = 2.

This means that in order for $\Delta\beta$ to completely negate $\alpha$, the slope of $\Delta\beta$ will need to be exactly half that of $\alpha$ and of opposite sign. The material compositions of the foil resistor and its cement and substrate allow accomplishing a very close ratio between $\alpha$ and $\Delta\beta$, which are key factors to the inherently low overall TCR.

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## CONCLUSIONS

Prediction of load life drift in foil resistors is based on evaluation of existing test data and can be performed using an Arrhenius type equation for calculation of the standard deviation of the drift. This equation is valid for loads not exceeding the rated power at a given ambient temperature by more than 60 %.

The mean value of the drift's distribution is in the range between –30 ppm and +100 ppm and depends on the resistor's history including its assembly.

A more precise value can be obtained by "burn in" and accelerated testing.

Based on the mean value and the calculated standard deviation, it is possible to calculate the maximum drift for load and ambient temperature and any desired confidence level (see an example above).

## ACKNOWLEDGEMENT

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**Note**