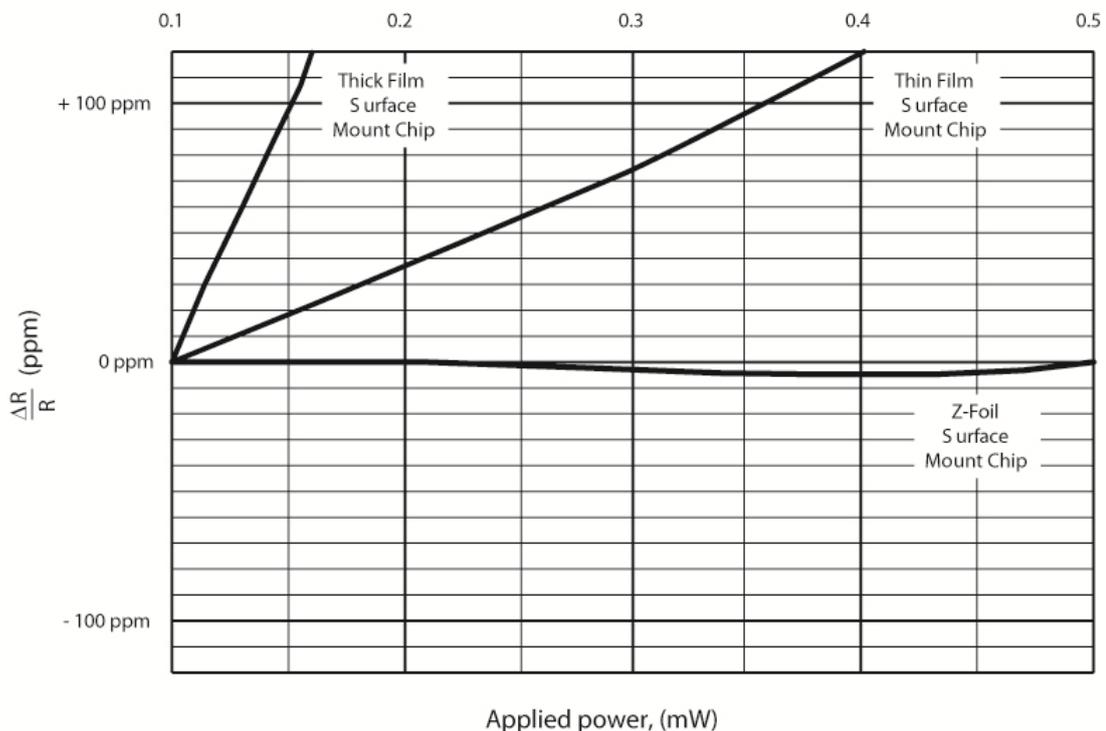


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Precision Resistors for Energy, Transportation, and High-Temperature Applications

The stability of a precision resistor depends primarily on its temperature, and temperature can affect resistor stability in many different ways. The thermally related effects on stability have different immediate, short-term, and long-term consequences, some of which are reversible and some of which are not.

The most immediate effect of an increase in temperature can be seen in the self-heating effect or power coefficient of resistance (PCR), which registers as a change in resistance as soon as the resistor heats up due to power dissipation. The second effect is the resistor's change as its body temperature changes due to temperature changes in its environment.



Note: Size 1206, value: 1K

Figure 1: Behavior of Three Different Resistor Technologies Under Applied Power (Power Coefficient Test)

Both of these changes are functions of the resistor's inherent temperature coefficient of resistance (TCR) responding to the resistor's body temperature, and both are independently and incrementally reversible when the power level is changed or the environmental temperature is changed.

The differences between the effects of TCR and PCR are small, but for TCRs in the very low ppm/°C range they are worth differentiating from one another so that design engineers can be empowered to exert as much control as possible over circuit stability in the most demanding applications.

Temperature also has an effect on the long-term operating stability, or load life, of the resistor. This is a permanent change in resistance, sometimes being so great as to cause complete resistor failure.

In this article, we are specifically concerned with the effects of temperature on *precision* resistors and the choices designers face in selecting the best precision resistor for high-temperature, energy, and transportation applications. While thick film resistor technologies are wide-spread and low cost, they are generally for commodity-oriented applications and are not considered for precision applications. Therefore, in this article, we compare only wirewound, thin film, and Bulk Metal® Foil resistor technologies with an eye towards how these have evolved with respect to extremes of temperature and other environmental factors such as moisture incursions, shock and vibration, low-temperature exposure, intermittent power surges, electromagnetic interference, switching pulses, and electrostatic discharge.

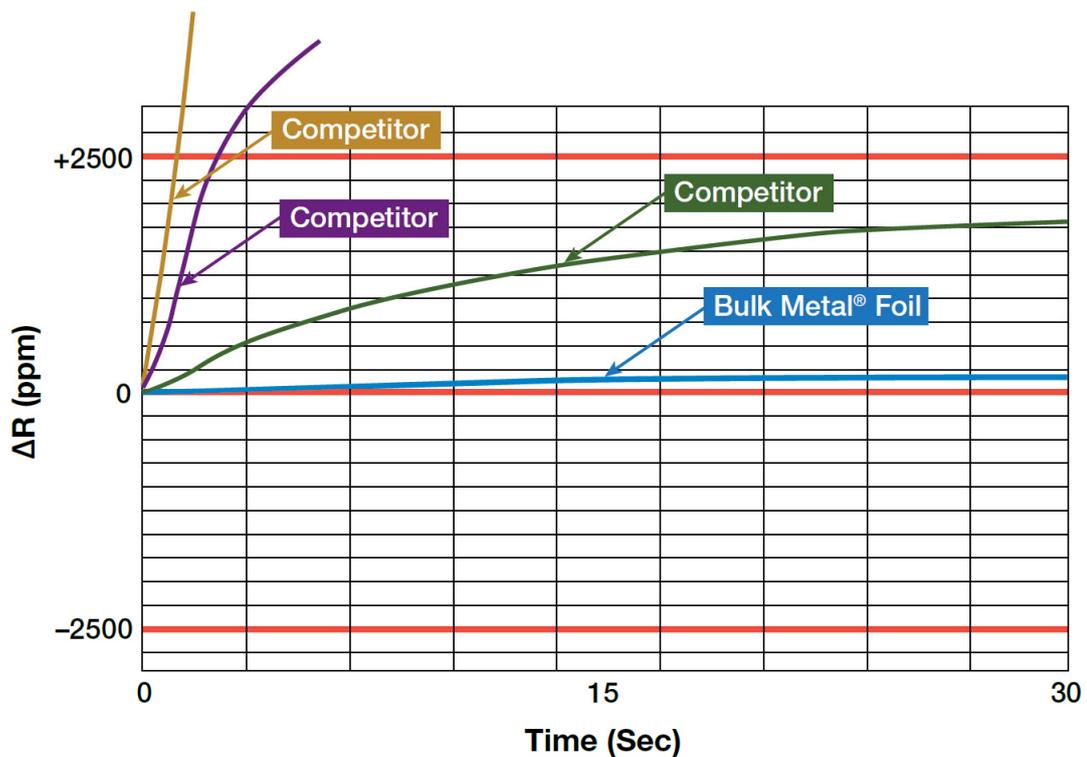


Figure 2: Thermal stabilization demonstration (1 W applied to 50 mΩ SMD 2512 – Current Sense)

The degree of precision for resistors is the extent to which they maintain their original value throughout these applications-related stress factors. The scramble for new technologies to improve efficiency in the energy industry continues to provide new opportunities for resistor manufacturers. In the petroleum market precision resistors are found in sophisticated seismographic instruments used in oil exploration, oil pipelines, and in computer-based process control instrumentation that drives petroleum refineries and chemical plants worldwide.

A typical commercial application for precision resistors might be such as in seismic exploration for petroleum and in the high-radiation, high-temperature environment of down-hole oil well data logging. In seismic oil exploration, resistors in analog circuits must not only be rugged but have fast response and excellent thermal stabilization characteristics to assure that no pulses are missed. They must not be sensitive to temperature changes and must track each other exactly so that the gain settings and ratios are predictable and reproducible over time. The resistors must also exhibit very low current noise to avoid “masking” seismically generated signals reflected from discontinuities in deep-earth strata where petroleum might reside. Amplifier modules must track with each other, since there may be many signal input channels in operation. Thus the phase shift between all amplifiers must be extremely tight. These requirements, and particularly TCR tracking, are absolute if the information collected from various parts of the world is to be later meaningfully compared.

Wirewound resistors can be placed into two categories: high-power, low-precision “power wirewounds,” and low-power, high-precision “precision wirewounds.” For our purposes, only the second category is of interest. Precision wirewounds are made from selected wire wound around a bobbin, moderately stress-relieved, calibrated to tolerance, and epoxy molded or hermetically sealed. The bobbin is divided along its length so as to allow sections, called pi-sections, to be wound in opposite directions to reduce inductance. However, even the best manufacturing techniques are only moderately effective in reducing inductance and wirewounds remain the resistors with the most reactance and highest phase shift.

The internal connections of wirewound resistors are also problematic. Solder is undesirable for the connections between the fine-wire resistive element and the large external terminals, and direct welding of the fine wire to the large terminals is generally unreliable. Thus the wire is almost always connected to the terminations through a transitional metal tab. The process-compatible metals available for the tabs introduce thermal EMF at the junctions, leaving wirewounds with relatively high thermal EMF among the precision resistors. Winding the wire requires tension to hold the wire in place, but this incorporates stresses that change during load-life, which in turn cause long-term resistance changes. Exposure to higher temperatures induces even greater resistance change over the device’s life. In their favor, wirewound resistors provide tighter tolerances and greater stability than thin film devices, but their weight and bulk limit their applications in high density electronics.

Thin film resistors are made by sublimating metallic films onto substrates using evaporative or sputtering processes to build up layers of metallic film. The film is then an agglomeration of metal particles with no independent monolithic structure apart from the substrate. Thin film resistors can achieve greater density in smaller packages than wirewounds because they can be made with higher resistance materials etched or laser-cut into fine pattern geometries.

The higher resistance comes primarily from the much smaller cross-sectional area of the thin film's very thin resistance grid, typically 1 square micron, compared to the finest useable wire with its 314 square microns being the smallest useable cross-sectional area.

Thin film resistors can also be made in flat substrate networks or compact resistor chip configurations that wirewounds cannot. They also have less reactance than wirewounds and are more suitable for higher frequency circuits than wirewounds. They are usually less costly than wirewounds as well.

The advantage of wirewounds over thin films is their lower TCRs and better long-term stability. The typical parabolic TCR curve of a thin film resistor can sometimes be rotated to be more horizontal over the warm temperature ranges above 25°C, but the concurrent negative effect is a worsening of the TCR in the temperature ranges below 25°C. Thin film resistors have greater current noise than wirewound resistors and exhibit considerably more shifts with high temperatures than other precision resistor technologies, in both TCR and long-term stability.

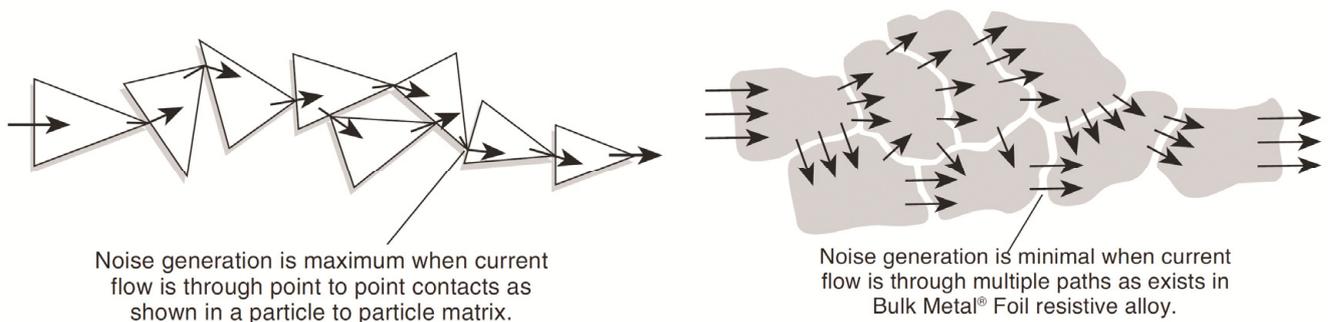


Figure 3: Noise Generation – Vishay Foil Resistor vs. Other Technologies

In the past, resistor development engineers attempted to improve resistor performance by reducing internal stresses in the components. For example, in precision wirewound resistors, they tried several methods to wind wire with enough winding tension to hold the wire in place and then reduce the stresses on the wire once it had been formed onto a bobbin. This was tricky enough to accomplish at the time of manufacture, but the process was unable to prevent the stresses from changing the resistance value after heating and cycling through actual in-circuit applications.

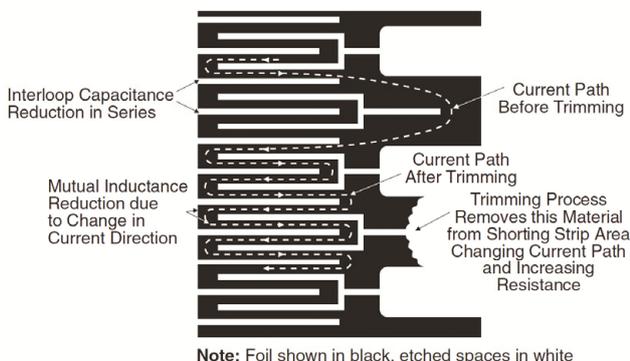
Thin film resistors do not have this option because thin film must be sputtered or deposited directly onto the substrate to form a new resistive agglomeration. So engineers making thin film resistors had two main options, to improve performance through screening or to give added protection to the film with coatings and encapsulants.

Foil resistor technology avoids many of these issues by managing stresses to counterbalance forces with opposing effects, thus utilizing those stresses to produce an extremely stable resistor. Rather than aiming for the lowest possible TCR, foil technology starts with a foil that has the most stable TCR over the widest temperature range. This TCR is achieved in a relatively thick, cold-rolled special alloy that maintains the same molecular structure as the raw alloy from which it is built. This allows the foil to act as a monolithic

structure with a fixed and known linear coefficient of thermal expansion (LCThE) over any temperature range the resistor might experience throughout its design life. The next most important element in the construction is the adhesive that holds the foil alloy to the flat ceramic substrate, while withstanding high temperatures and other phenomena such as pulsing power, moisture incursions, shock and vibration, low-high temperature exposure, and electrostatic discharge (ESD) while holding the foil element securely to the substrate.

These characteristics comprise the essential stress compensation that defines foil technology. With an increase in temperature the unbonded foil has an inherent increase in resistance (positive TCR). Concurrently, the foil experiences a compressive force because its higher LCThE is pushing it against the restraining force of the substrate. This compressive force drives the resistance down. With an increase in temperature, this perfectly balanced duality works to drive the resistance down (the compressive force) by the exact same amount of inherent increase in resistance (the positive TCR of the unbonded foil), resulting in a near-zero TCR of the finished resistor. This yields foil resistors with TCRs of less than 1 ppm/°C.

The flat planar structure of the foil resistor, with the resistance element at the surface (before coating or encapsulation), lends itself to a unique process for trimming resistors to value in order to avoid hot spots and compressed current density where the resistance grid changes direction. Tolerances as tight as 0.001% can be achieved in hermetically-sealed packages. The foil resistor element is photo-etched with a grid that incorporates geometrically proportioned successive links that can be removed while incrementally increasing resistance in successively smaller amounts without introducing excess noise or randomly distributed current density compression (hot spots). The grid is further designed with opposing currents in adjacent paths so as to minimize both inductance and capacitance for high-speed performance. Using these basic technology innovations, the resistor can be completed in many different configurations, including power resistors, current sense resistors, hermetically sealed metrology resistors, surface-mount chip resistors with stress-isolating flexible terminations, and many more for applications in space and aviation, medical equipment, process controls, or wherever high-precision resistors, networks, and trimming potentiometers need to work under conditions of extreme temperature.



To acquire a precision resistance value, the Bulk Metal[®] Foil chip is trimmed by selectively removing built-in “shorting bars.” To increase the resistance in known increments, marked areas are cut, producing progressively smaller increases in resistance. This method reduces the effect of “hot spots” and improves the long term stability of the Vishay Foil chips.

Figure 4: Trimming to Values (Conceptual Illustration)

Now, looking back at the seismic petroleum exploration and the oil well data logging applications, the new Z1-Foil Bulk Metal® Foil resistors assure virtually noise-free operation. They offer predictable responses and very precise tracking of amplifiers within an individual system or among several interrelated systems. When resistors such as these have near-zero TCRs, it means that resistors in different circuits at different temperatures in different equipment maintain consistent relationships even when geo-physically separated.

Z1-Foil resistors, the latest state-of-the-art in foil resistor technology, excel over all previous stability standards for precision resistors with an order of magnitude improvement in temperature stability, load-life stability, and moisture resistance, all of which become more critical in our unpredictable global climate—whether they're operating in the high-humidity heat of the jungle, in the dry cold environment of the arctic, or in a fighter jet where they will encounter the shock and vibration of take-off and a temperature shift from +120°F (+49°C) on the desert floor to -55°F (-48°C) at cruising altitude in less than a minute with virtually no change in resistance. These new benchmark levels of performance provide design engineers with the tools to build analog circuits not previously achievable, while reducing costs in the most critical circuits by eliminating the need for corrective circuitry used only for the purpose of stabilizing or iterating accuracy in successive stages of the circuit path.

Before Z1-Foil technology, high-frequency precision applications were only served by precision thin film resistors, but these devices are not as accurate or as stable as wirewound resistors, which do not have good high-frequency response. This new, fourth generation of foil technology presents designers with resistive components that offer even higher precision than wirewounds while being well-suited for high-frequency and high-temperature applications. Foil enables significant size reductions as well. Now Bulk Metal® Foil resistors in sizes as small as 0603 can serve as on-board secondary standards going anywhere the equipment goes—even into deep space. The new Z1-Foil FRSH, HTHG, and HTHA series of surface-mount chip resistors exemplify this innovative new technology that can withstand temperatures up to 240°C, while the highest level of precision and stability is exemplified by the new FRSM series.

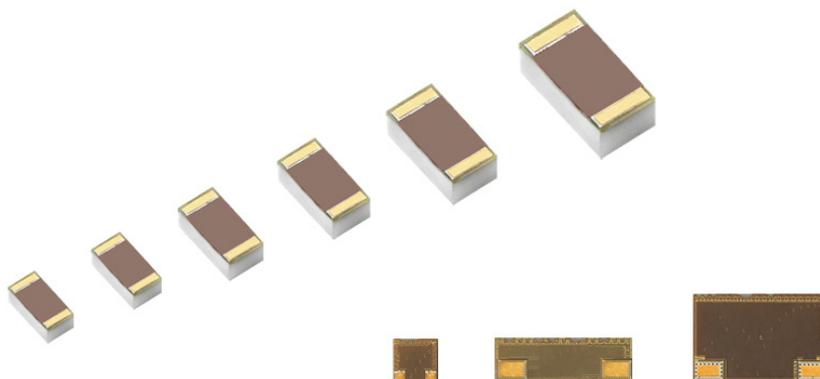


Figure 5: HTHG and HTHA Package Size Options

Reducing circuit area introduces new design challenges associated with thermal management and its unintended consequences, and in some cases greater sensitivity to ESD. One such problem is the thermal electromotive force (ThEMF) that introduces error voltages wherever temperature differentials exist between two junctions of two dissimilar metals, such as where internal resistive elements are joined to the external terminations of a resistor. Temperature differentials are developed across a resistor by uneven internal power dissipation, terminations heated by heat-radiating components, and from thermal dissipation paths running along the circuit board in both the conductive paths and the baseboard material itself. The foil devised for its innate TCR and its LCThE also has a very low thermal EMF compared to copper of only $0.05 \mu\text{V}/^\circ\text{C}$.

For more information about this product group, please contact us at: Foil@vishaypg.com

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