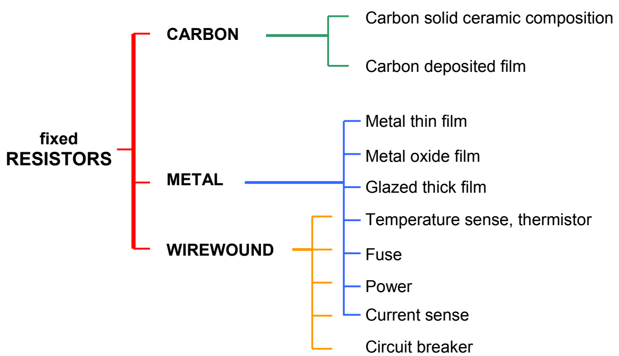
25

Resistors

Power resistors (≥1W) are used extensively in power electronic circuits, either as a pure dissipative element, or to provide a current limiting path for charging/discharging currents. Depending on the application, these energy transfer paths may need to be either inductive or non-inductive. Power resistors are used for the following non-inductive resistance applications.

- Series *R-C* circuit for diode, mosfet and thyristor snubbers (non-inductive) (6.1.2,8.1, 8.3)
- Series turn-on *L-R-D* snubbers (6.1.2, 8.3.3)
- *R-C-D* turn-off snubbers for GTO thyristors - inductance in *R* is allowable (8.2)
- Static voltage sharing for series connected capacitors and semiconductors (10.1.1)
- Static current sharing for parallel connected semiconductors (10.1.2)
- Resistor divider for proportional voltage sensing (10.2.3)
- Current sensing (10.2.3)
- Damping, clamping, and voltage dropping circuits

The resistive element specification can be more than just fulfilling resistance and power dissipation requirements. For example, a current shunt resistor should be non-inductive in order to give good high frequency performance. Conversely, the resistor of the *R-C-D* turn-off snubber considered in 8.3 can be inductive thereby reducing the high initial peak current associated with an *R-C* discharge. An important resistor requirement is working voltage and the dielectric withstand voltage. High voltages (>200 V) are common in power circuits and the physical construction of a resistor places a limit to allowable voltage stress levels. Certain applications within the realm of power electronics may necessitate a power resistor with a low temperature coefficient of resistance (or even a negative temperature coefficient), a high operating temperature, a high pulse power ability or even a low thermoelectric voltage. Any one of these constraints would restrict the type and construction of resistor applicable.



25.1 Resistor types

The resistor tree illustrates the main types of resistors used in electrical power applications. The three main resistor types are carbon/metal film, solid, and wire wound. The main electrical and thermal properties of each resistor type are summarised in table 25.1. Typical property values for power resistors are shown, which may vary significantly with physical size and resistance value.

25.2 Resistor construction

Almost all types of power resistors (≥1W) have a cylindrical high purity ceramic core, either rod or tube as shown in figure 25.1. The core has a high thermal conductivity, is impervious to moisture penetration, is chemically inert, and is capable of withstanding thermal shock. The resistive element is either a carbon film, a homogeneous metal-based film or a wound wire element around the ceramic body. For high accuracy and reliability, a computer-controlled helical groove is cut into the film types in order to trim the required ohmic resistance. The resistance tolerance can be typically ± 5% for wire wound resistors and better than ± 0.1% for trimmed film types.
The terminations are usually nickel-plated steel, or occasionally brass, force fitted to each end of the cylindrical former in order to provide excellent electrical and thermal contact between the resistive layer and the end-cap. Tinned connecting wires of electrolytic copper or copper-clad iron are welded to the end-caps, thereby completing the terminations. Axial cylindrical resistors without leads, used as surface mount resistive devices (SMD), are termed *metal electrode leadless face*, MELF.
All fixed resistance resistor bodies are coated with a protective moisture-resistant, high dielectric field strength, and some times conformal coating, such that the wire terminations remain clear and clean.
The resistors are either colour coded by colour bands or provided with an identification stamp of alphanumeric data.

Table 25.1: The main characteristics of electrical power resistors

			carbon composition	carbon deposited film	metal thin film	glazed thick film LV	glazed thick film HV	metal oxide film	power wire wound	fusible	circuit breaker	temperature sense	current sense
Resistance range	R	Ω	10-22M	1-10M	1-5M	1-2M	300k-1G	15-100k	0.1-1.5M	0.1-3.9k	0.27-82k	0.1-300	0.01 - 10
Watts @ 70°C	P_R	W	1	2	2.5	2	90	7	>300	2	6	2	9
Maximum temperature	T_h	°C	150	125	300	175	100	235	275	160	150	200	250
Working voltage	V_m	V	500	500	500	1k	100k	650	2.5k	160	500	700	$\sqrt{PR}$
Voltage coefficient	φ	10^{-6}/ V	200	50	5	10	-	0.1	<1	-	-	-	-
Residual capacitance	C_R	pF	¼	½	-	-	$\frac{1}{5}$	½	-	-	-	-	-
Temperature coefficient	α	10^{-6}/ K	-500 -1000	+50 -350	±350	±200	±150	±500	50	500	-80 +500	-3000 +5500	100
Thermal resistance	R_θ	K / W	80	27	90	35	13	26	0.3	50	14	0.55	20
Reliability	λ	10^{-9}/hr fit	1	10	1		-	3	300	-	-	-	-
Stability $\frac{\Delta R}{R}$%	@ P_R, T_a = 70°C, @10^3 hours		5	3	5	½	2	3	3	5	2 @ 150°C	0.1	3
Tolerance %			10	5		1	1	1		0.1			

25.2.1 *Film resistor construction*

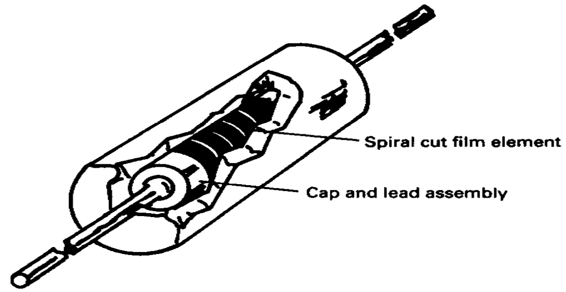
Figure 25.1a shows a sectional view of a typical film resistor having a construction as previously described. The resistive film element is produced in one of four ways:

- cracked carbon film
- glaze of glass powder mixed with metals and metal compounds fired at 1000°C, giving a firmly bonded glass-like film on the core

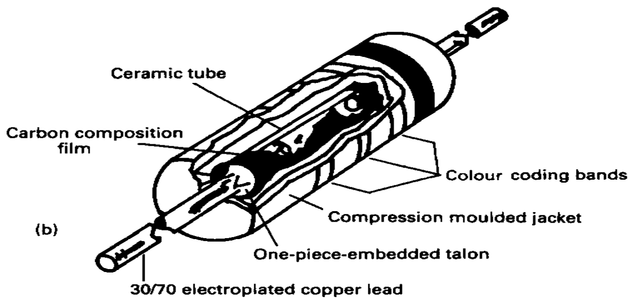
- precisely controlled thin film of metal alloy (Cr/Ni or Au/Pt) evaporated, baked or vacuum sputtered (vacuum deposition) on to the inert core and of thickness between 10^{-8}m and 10^{-7}m
- metal oxide ($Sn0_2$) resistive film deposited or sintered on to the core.

The film materials exhibit a wide range of resistivity, ρ, which extends from 40 × 10^{-6} Ω cm for gold/platinum to in excess of 10^2 Ω cm for layers of thick film mixture. The thinnest possible film, for maximum resistance, is limited by the need for a cohesive conductive film on the ceramic substrate while the thickest film, for minimum resistance, is associated with the problem of adhesion of the resistance film to the substrate.
The helical groove shown in figure 25.1a, used to trim resistance (by increasing the length of the film width), is shown clearly and is either laser or diamond (abrasive) cut. The residual inductance is significantly increased because of the formed winding which is a spiral around the core. Below 100 Ω, a helical groove may not be used.
The difference between thick and thin film is how the film is applied (not necessarily the film thickness).

(a)



(b)



0	black	
1	brown	±1%
2	red	±2%
3	orange	
4	yellow	
5	green	±½%
6	blue	±¼%
7	violet	$\pm\frac{1}{10}$%
8	grey	$\pm\frac{1}{20}$ %
9	white	
$\times\frac{1}{10}$	gold	±5%
$\times\frac{1}{100}$	silver	±10%

(d)

(c)

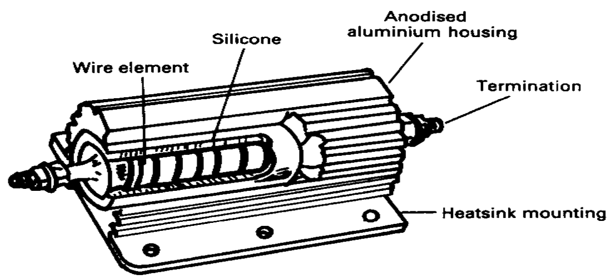


Figure 25.1. *Power resistor construction: (a) metal glaze, thick film; (b) moulded carbon composition film; (c) wire wound aluminium clad; and (d) resistance colour code and tolerances.*

Thick film, as used for low cost surface mount (SMD) resistors, employs traditional liquid screen printing technology baked at 850°C, as opposed to spluttering type technology for thin film resistors.
As a result thin film resistors are

- more expensive than thick film resistors
- have better tolerances, typical 0.1% to 1% and a temperature coefficient of ±5 to ±25 ppm, because the spluttering time can be used to control the film thickness

Thick film tolerances are typically: 1 to 2% on resistance and a temperature coefficient of ±200ppm.

Resistive materials such as polymer and ruthenium oxide RuO_2 are used for high voltage and high resistance resistors up to 100 kV, 1 GΩ and 20 kV, 150 GΩ respectively. Ruthenium oxide is called a *cermet* since it is a composite of a *cer*amic and a *met*al. At lower voltage ratings, the same oxide is used to produce planar thick film power resistors, which are mounted on an alumina substrate to give a low thermal resistance for better cooling. The planar strip structure gives a low inductance element with a high surface area for better heat transfer. Dissipation levels of over 200W, up to 900W, are possible when packaged in TO220, ISOTOP, etc. type packages, which can be heatsink mounted.

25.2.2 Carbon composition film resistor construction

A sectional view of a moulded carbon composition film resistor is shown in figure 25.1b. The resistive carbon film is cured at 500°C and is unspiralled, hence non-inductive with excellent high frequency characteristics. The resistance value is obtained by variation of film composition and thickness, which may be between 0.01 µm and 30 µm. A component with a wide nominal value tolerance results since the film is not helically trimmed.
A special formed one-piece talon lead assembly is deeply imbedded into the substrate for good uniform heat dissipation. These terminations are capless.
The following example illustrates typical parameters and dimensions for carbon film resistors.

Example 25.1: ***Carbon film resistor***

A 470 Ω resistor is constructed from a film of carbon with a resistivity 3.5 × 10^{-5} Ω m, deposited on a non-conducting ceramic bar 3 mm in diameter and 6 mm long.
Calculate the thickness of film required, ignoring end connection effects.

Solution

Let thickness of the film be t metre, then

$$\text{cross-sectional area} \approx \pi \times 3 \times 10^{-3} \times t \quad (m^2)$$

Now $R = \rho\ell/\text{area}$, that is

$$470\Omega = 3.5\times10^{-5}\times6\times10^{-3}/\pi\times3\times10^{-3}\times t$$

$$t = 0.0474\ \mu m$$

♣

25.2.3 Solid carbon ceramic resistor construction

Mixtures of finely ground, powdered clay, alumina, and carbon are blended with resin, pressurised (moulded) into the desired shape (diameters from less than 0.3mm to over 15mm), and fired in a tunnel kiln, at high temperature and controlled pressure. The higher the carbon concentration, the higher the resistivity (resistance). This sintering process results in a 100% active homogeneous, solid volume resistive element, in a minimum size. Aluminium (and/or brass, silver, nickel) is then flame-sprayed on to the appropriate surfaces to provide electrical contact, followed by gold plated spring pin terminations, if to be used for pcb mounting. Then an anti-tracking epoxy resin coating is applied using a fluidised bed technique, to improve dielectric withstand, mechanical robustness, and minimise corrosion. Although the coating reduces the rate of moisture ingress, the element is not impervious to liquid, so after drying for 24 hours at 110-120°C, it is silca gel coated if the resistor is to be immersed in SF_6 gas or oil.
Because of the solid construction, the ceramic carbon element has a high surge energy pulse rating, high voltage withstand, high transient voltage impulse withstand, inherent low inductance, higher thermal capacity, and is mechanical robust; with compact size and a wide range of geometries. It is brittle to direct mechanical impact. Also, because of its homogeneous physical and chemical structure, resistor mechanical, electrical, and thermal properties and characteristics can be defined mathematically or empirically. At high electrical stress levels, the resistivity property change. Mechanical, thermal, and electrical data is presented in Appendix 25.8 for solid ceramic carbon. Rod, disc, and tube shapes are common, with resistance tolerances of not better than ±5%.

25.2.4 Wire-wound resistor construction

The sectional view of an aluminium-housed power wire-wound resistor, shown in figure 25.1c can dissipate up to 300 W with a suitable heatsink in air or up to 900 W when water-cooled.
The central former is a high purity, high thermal conductivity ceramic, of either Steatite or Alumina tube, depending on size. The matching resistive element is iron-free, 80/20 nickel-chromium for high resistance values or copper-nickel alloy for low resistance. These alloys result in a wire or tape which has a high tensile strength and low temperature coefficient. The tape or wire is evenly wound on to the tube former with a uniform tension throughout. This construction is inductive but gives a resistor which can withstand repeated heat cycling without damage.
The assembled and wound rod is encapsulated in a high temperature thermal conducting silicone moulding material and then cladded in an extruded, hard, anodised aluminium housing, ensuring electrical and thermal stability and reliability.
Alternatives to the aluminium-clad resistor are to encapsulate the wound rod in a vitreous enamel or a fire-proof ceramic housing.
Power wire-wound resistors with a low temperature coefficient, of less than $\pm 20\times10^{-6}$ /K, use a resistive element made of Constantan (Nickel and Copper) or Nichrome (Nickel and Chromium). Constantan is used for lower resistance, up to several kilo-ohm, while Nichrome is applicable up to several hundred kilo-ohm. The resistance ranges depend on the ceramic core dimensions, hence power rating. The element is wound under negligible mechanical tension, resulting in a reliable, low temperature coefficient resistor which at rated power can safely attain surface temperatures of over 350°C in a 70°C ambient. Because these resistors can be used at high temperatures, the thermally generated emf developed at the interface between the resistive element and the copper termination can be significant, particularly in the case of Constantan which produces -40 μV/K. Nichrome has a coefficient of only +1 μV/K, while gold, silver, and aluminium give +0.2, -0.2, and -4 μV/K, respectively, when interfacing with copper. EMF polarities cancel with identical resistor terminations.

Ayrton-Perry wound wire elements can be used for low inductance applications. The resistive element is effectively wound back on itself, after an insulation layer, such that the current direction in parallel conductors oppose and cross every 180°. Also a bifilar winding or an opposing chamber winding can be used. The net effect is that a minimal magnetic field is created, hence residual inductance is low. The maximum resistance is one-quarter that for a standard winding, while the limiting element voltage is reduced, by dividing by √2. The low inductance winding method is ineffective below 4.7Ω. This winding style also lowers the maximum permissible winding temperature, called *hot spot temperature*, T_h. The hot spot temperature is the resistor surface temperature at the centre of its length.

25.3 Electrical properties

An electrical equivalent circuit for a wirewound resistor is shown in figure 25.2. The ideal resistor is denoted by the rated resistance, R_R, and the lumped residual capacitance and residual inductance are denoted by C_r and L_r respectively. A film type resistor is better modelled with the capacitor in parallel with the resistive component.
The terminal resistance of a homogeneous element of length ℓ and area A is given by

$$R(v,f,T)=\rho(v,f,T)\frac{\ell}{A}=\frac{\ell}{\sigma A} \qquad (\Omega) \qquad (25.1)$$

where ρ is the resistivity of the resistive element and σ is the conductivity (= $1/\rho$).
The total effective resistance of series and parallel connected resistive elements are given by

$$R_s=R_1+R_2+R_3+\ldots$$
$$\frac{1}{R_p}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\ldots \qquad (25.2)$$

$$Z=\frac{R_R}{\dfrac{R_R^2}{X_{Cr}^2}+\dfrac{(X_{Lr}-X_{Cr})^2}{X_{Cr}^2}}+j\,\frac{X_{Lr}-\left[\left(R_R^2+X_{Lr}^2\right)/X_{Cr}\right]}{\dfrac{R_R^2}{X_{Cr}^2}+\dfrac{(X_{Lr}-X_{Cr})^2}{X_{Cr}^2}}$$

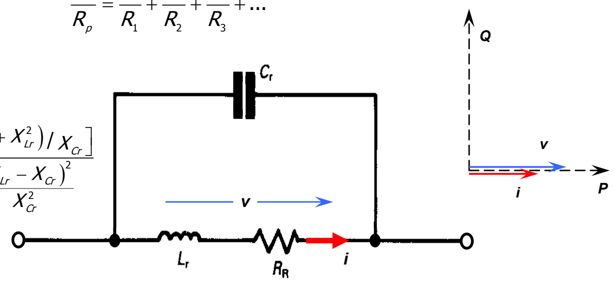


Figure 25.2. *Equivalent circuit model of a resistor.*

The terminal resistance is a function of temperature, voltage, and frequency. Temperature dependence is due to the temperature dependence of resistivity α, typical values of which are shown in table 25.1. The temperature coefficient may vary with either or both temperature, as with carbon and metal film resistors, or resistance, as with thick film and noble metal film resistors. A reference for measurement is usually 25°C. Frequency dependence is due to a number of factors, depending on the type of resistive element and its resistance value. Typical factors are due to skin effects in the case of wire-wound resistors or residual capacitance in film types. Frequency dependent resistance, R_{ac}, for carbon composition film and metal glaze thick film resistors, is shown in figure 25.3.
A voltage dependence factor, which is called ϕ, is given in table 25.1 and is resistive element type dependent. For operation at low frequencies, resistance is given by

$$R(v,T)=R(0,25^\circ\mathrm{C})(1+\phi v)(1+\alpha T) \qquad (\Omega) \qquad (25.3)$$

Values for linearity coefficients ϕ and α are given in table 25.1.

Ideally, electrically, the terminal voltage and current are in phase and related by Ohm's law, namely

$$v=i\times R \qquad (\mathrm{V}) \qquad (25.4)$$

where it is usually assumed that R is constant. This electrical relationship is shown in the phase diagram in figure 25.2. In practice when a pure sinusoidal current is passed through a resistor, its terminal voltage may not be a pure sinusoid, and may contain harmonic components. This voltage distortion is termed nonlinearity and is the harmonic deviation in the behaviour of a fixed resistor from Ohm's law, equation (25.4). Another resistor imperfection is *current noise* which is produced by the thermal agitation of electrons due to resistive element conductivity fluctuation. The noise voltage is proportional to current flow. Johnson noise is given by $E_{rms}^{noise}(t)=\sqrt{4k\,RT\,\Delta f}$, where Δf is the measurement bandwidth and k is Boltzmann's constant. Wire-wound resistors generate negligible current noise. The resistance value itself can change: *long term drift* due to chemical-physical processes such as oxidation, re-crystallisation corrosion, electrolysis, and diffusion, as may be appropriate to the particular resistive element.

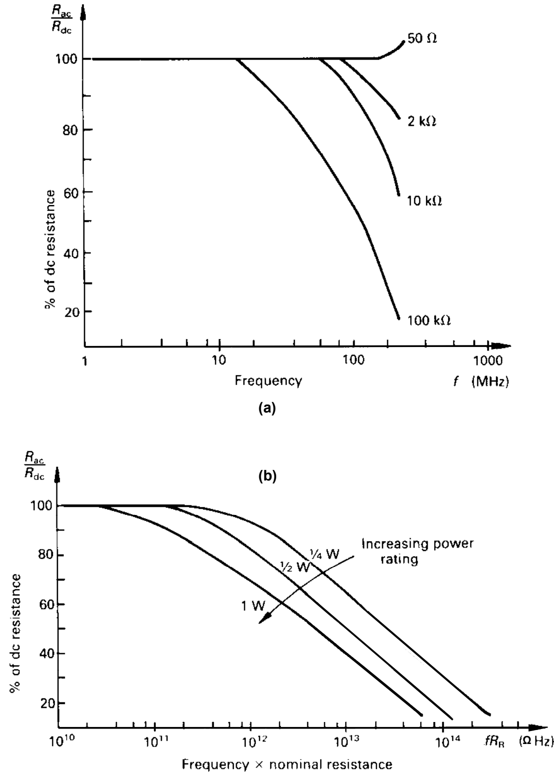


Figure 25.3. *Resistor high frequency characteristics: (a) of a metal glaze thick film 3 W resistor and (b) moulded carbon composition film resistors.*

The power dissipated, P_d, in an ideal resistor, in general, is specified by

$$P_d = v\,i = i_{rms}^2 R = v_{rms}^2 / R \qquad \text{(W)} \qquad (25.5)$$

where the power dissipated is limited by the power rating, P_R, of the resistor. In turn, the power limit may also set the maximum voltage that can be withstood safely. Joules law of heat generated is $Q=I^2Rt$.

25.3.1 Resistor/Resistance coefficients

Three mechanical, thermal or electrical coefficients are relevant to a resistor and its resistance

- coefficient of linear expansion
- temperature coefficient of resistance, α
- voltage coefficient of resistance, Φ

The coefficient of linear expansion is only relevant to solid carbon ceramic type resistors. It is dependant on resistivity, ρ, and is in the range $+4\times10^{-6}$ to $+10\times10^{-6}$ /°C. The voltage and temperature coefficients of resistance are also dependant on the resistivity of the resistive element.

25.3.1i - Temperature coefficient of resistance - α

The resistance temperature coefficient α in equation (25.3) and in table 25.1 should not be taken as to imply a linear relationship between temperature and resistance, $1+\Phi\times v$. Contrarily, for simplicity, it is only a linear approximation to a quadratic approximation of a non-linear function, as shown in figure 25.4. This figure shows the resistance behaviour of a typical thick film resistor, with varied temperature. The lower the temperature coefficient, the flatter the resistance-temperature curve. The temperature dependant relationship is modelled by a quadratic equation:

$$R(T) = R_o + \mathrm{a}T^2 + \mathrm{b}T + \mathrm{c} \qquad (25.6)$$

where a, b, and c are the quadratic coefficients and R_o is the minimum resistance value, which for this resistor type, usually occurs around 35°C. The temperature at which the minimum resistance R_o occurs can be varied by changing the resistor chemical composition. The temperature co-efficient α is related to the slope $\Delta R/\Delta T$ and is defined by

$$\alpha(T) = \frac{R(T) - R(25°\mathrm{C})}{\Delta T \times R(25°\mathrm{C})} \times 10^6 \quad = \quad \frac{\Delta R}{\Delta T} \times \frac{10^6}{R(25°\mathrm{C})} \qquad \left(10^{-6}/°\mathrm{C} \;\text{ or }\; \mathrm{ppm}/°\mathrm{C}\right) \qquad (25.7)$$

Given the normal temperature operating range for resistors, it is usual when characterising resistors, to use 25°C as a reference with a +50°C temperature change, that is ΔT = +50°C. The resultant resistance change for this ΔT = +50°C defines the temperature co-efficient. It will be seen that the definition coefficient slope is not necessarily the maximum slope in the range 25°C to 75°C.

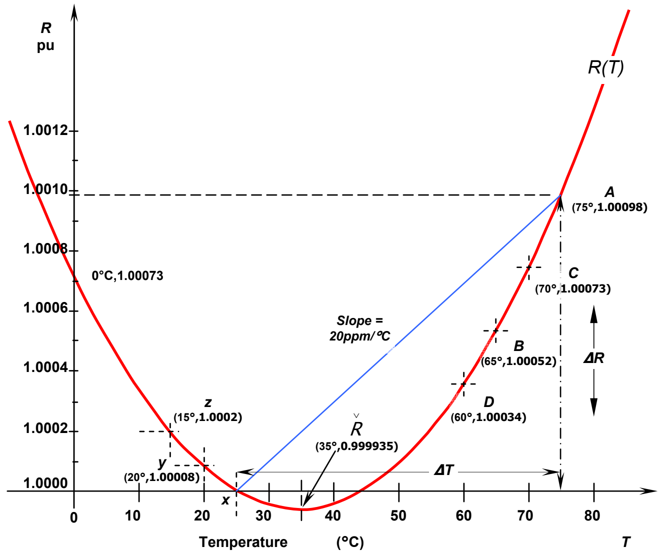


Figure 25.4. *Typical temperature characteristics of resistance for thick film resistors.*

Alternatively, solid carbon ceramic resistive elements may have a temperature coefficient defined in terms of resistivity (in Ω-cm), as an empirical formula such as:

$$\alpha = +1600 \times e^{-\log\rho/1.4} - 1350 \qquad \left(10^{-6}/°\mathrm{C} \;\text{ or }\; \mathrm{ppm}/°\mathrm{C}\right) \qquad (25.8)$$

Example 25.2: ***Temperature coefficient of resistance for a thick film resistor***

Figure 25.4 shows a quadratic approximation for the variation of per unit resistance with temperature, with a minimum resistance of 0.999935pu occurring at 35°C, and 1pu resistance at 25°C and 45°C.

Determine:

i. suitable model quadratic coefficients a, b, c
ii. the 0°C pu resistance
iii. the temperature co-efficient of resistance based on ΔT = +50°C and ΔT = +40°C and the resistance change in each case, with a 25°C reference, point *x*
iv. the incremental temperature coefficient over the range 25°C to 75°C
v. the temperature co-efficient of resistance based on ΔT = +50°C and ΔT = +40°C and the resistance change in each case, with a 20°C reference, point *y*
vi. the minimum resistance occurs at 45°C, with the identical shape. Determine the resistance temperature coefficient (ΔT = 75°C - 25°C) of the resultant resistor

Solution

i. Assuming the temperature dependant resistance data in figure 25.4 is curve fitted by a best fit quadratic, then that quadratic has roots at T = 25°C and T = 45°C, thus after shifting the Y-axis (R_{pu}) by 1pu:

$$R_{pu} - 1 = \mathrm{a}(T - 25°\mathrm{C})(T - 45°\mathrm{C})$$

To ensure accuracy in the normal operating range, the minimum resistance point $\check{R}$, (35°C, 0.999935) is used to find the second order temperature term co-efficient, and

$$R_{pu} - 1 = \mathrm{a} \times (T - 25°\mathrm{C})(T - 45°\mathrm{C})$$

$$0.999935 - 1 = \mathrm{a} \times (35°\mathrm{C} - 25°\mathrm{C})(35°\mathrm{C} - 45°\mathrm{C}) \quad \Rightarrow \quad \mathrm{a} = 6.5 \times 10^{-7}$$

The quadratic coefficients are thus

$$R_{pu} - 1 = 6.5 \times 10^{-7} \times (T - 25°\mathrm{C})(T - 45°\mathrm{C})$$

$$R_{pu} - 1 = 6.5 \times 10^{-7} T^2 - 4.55 \times 10^{-5} T + 7.3125 \times 10^{-4} \quad \text{or}$$

$$R_{pu} = 6.5 \times 10^{-7} T^2 - 4.55 \times 10^{-5} T + 1.00073125$$

ii. Substituting 0°C into the quadratic gives the constant c, that is 1.000731 - 0.999935 = 0.00080, as can be confirmed from the best fit plot in figure 25.4.

iii. When using 25°C as the parameter specification reference, point x, the quadratic is used to give the pu resistance at points A (75°C) for ΔT = +50°C and B (65°C) for ΔT = +40°C shown in figure 25.4.

For point A:

$$\alpha_{\Delta T = 50°C}^{T_o = 25°C} = \frac{R_{pu-A} - R_{pu-a}}{T_A - T_a}$$

$$= \frac{1.00098\text{pu} - 1\text{pu}}{75°\mathrm{C} - 25°\mathrm{C}} = 19.6 \times 10^{-6}\,(/°\mathrm{C}) \quad \text{or} \quad 19.6\text{ppm}/°\mathrm{C}$$

For point B:

$$\alpha_{\Delta T = 40°C}^{T_o = 25°C} = \frac{R_{pu-B} - R_{pu-a}}{T_B - T_a}$$

$$= \frac{1.00052\text{pu} - 1\text{pu}}{65°\mathrm{C} - 25°\mathrm{C}} = 13.0 \times 10^{-6}\,(/°\mathrm{C}) \quad \text{or} \quad 13\text{ ppm}/°\mathrm{C}$$

iv. The tangential slope to the quadratic is the differential of the quadratic:

$$\alpha = 13.0 \times 10^{-7} \times T - 4.55 \times 10^{-5}$$

$$\alpha_{25°C} = 13.0 \times 10^{-7} \times 25°\mathrm{C} - 4.55 \times 10^{-5} = -13\text{ ppm}/°\mathrm{C}$$

$$\alpha_{35°C} = 13.0 \times 10^{-7} \times 35°\mathrm{C} - 4.55 \times 10^{-5} = \;\; 0\text{ ppm}/°\mathrm{C}$$

$$\alpha_{75°C} = 13.0 \times 10^{-7} \times 75°\mathrm{C} - 4.55 \times 10^{-5} = +52\text{ppm}/°\mathrm{C}$$

The temperature coefficient ranges from -13 to 52 ppm/°C.

v. When using 20°C as a parameter specification reference, point *y*, the quadratic is used to give the pu resistance at points C, ΔT = +50°C, and D, ΔT = +40°C, shown in figure 25.4.

For point C:

$$\alpha^{T_o=20^\circ C}_{\Delta T=50^\circ C} = \frac{R_{pu-C}-R_{pu-b}}{T_A-T_a}$$

$$= \frac{1.00073\text{pu} - 100008\text{pu}}{70^\circ\text{C}-20^\circ\text{C}} = 13.0\times10^{-6}\ (/^\circ\text{C}) \quad \text{or} \quad 13.0\ \text{ppm}/^\circ\text{C}$$

For point D:

$$\alpha^{T_o=20^\circ C}_{\Delta T=40^\circ C} = \frac{R_{pu-D}-R_{pu-a}}{T_D-T_a}$$

$$= \frac{1.00034\text{pu} - 100008\text{pu}}{65^\circ\text{C}-25^\circ\text{C}} = 6.5\times10^{-6}\ (/^\circ\text{C}) \quad \text{or} \quad 6.5\ \text{ppm}/^\circ\text{C}$$

vi. The data for a shift of the minimum resistance from 35°C to 45°C can be obtained by considering the appropriate quadratic graph translation. The point z becomes the new 25°C reference and the 50°C temperature increase point becomes data point B.

$$\alpha^{T_o=15^\circ C}_{\Delta T=50^\circ C} = \frac{R_{pu-B}-R_{pu-c}}{T_B-T_c}$$

$$= \frac{1.00052\text{pu} - 1.0002\text{pu}}{65^\circ\text{C}-15^\circ\text{C}} = 6.4\times10^{-6}\ (/^\circ\text{C}) \quad \text{or} \quad 6.4\ \text{ppm}/^\circ\text{C}$$

♣

25.3.1ii - Voltage coefficient of resistance - Φ

The voltage coefficient of resistance is resistivity, ρ, dependant and usually assumed linear for simplicity. For resistors intended for high voltage application, such as carbon ceramics, more accurate voltage dependence is necessary and element length dependant, empirical formula are provided, for example

$$\phi = -0.62\times\rho^{0.22} \qquad (\%/\text{kV/cm}) \tag{25.9}$$

where resistivity, ρ, is in Ω-cm.

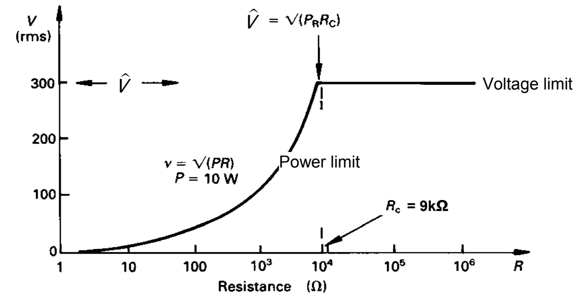


Figure 25.5. *Resistor voltage limits for a given power rating.*

25.3.2 Maximum working voltage

The maximum working voltage $\hat{V}$, either dc or ac rms, is the limiting element voltage that may be continuously applied to a resistor without flashover, subject to the maximum power rating P_R not being exceeded. A typical characteristic is shown in figure 25.5, which illustrates the allowable voltage bounds for a 10 W resistor range, having a limiting flashover voltage of 300 V rms.

At lower resistance, power dissipation capability limits the allowable element voltage, and above a certain resistance level, termed *critical resistance*, R_c, the maximum working voltage, $\hat{V}$, is the constraint. Maximum working voltage decreases with decreased air pressure, typically a 30 per cent reduction for low pressures.

Resistive elements intended for high voltage and surge applications have the maximum working voltage more rigorously defined, and for different possible operating conditions. The following empirical expressions are valid for high pulse energy rated, solid carbon ceramic resistors. It will be seen that the maximum working voltage is fundamentally a property of resistivity, not resistance.

For voltage pulses in the range of t =10ms to 50ms, the maximum working voltage per cm of resistor length is

$$\hat{V} = 1.00\times\left(\frac{\rho}{t}\right)^{0.335} = 1.00\times\left(\frac{R}{t}\frac{A}{\ell}\right)^{0.335} \quad (\text{kV / cm}) \text{ in SF}_6 \text{ gas}$$

$$\hat{V} = 0.87\times\left(\frac{\rho}{t}\right)^{0.3} = 0.87\times\left(\frac{R}{t}\frac{A}{\ell}\right)^{0.3} \quad (\text{kV / cm}) \text{ in air} \tag{25.10}$$

Low resistance values (<100Ω):

For transient impulse voltages across low resistances, the maximum working voltage per cm of length is

$$\hat{V} = 8.0\times\sqrt[1.2]{\log\left(\frac{\rho}{2.54}\right)} = 8.0\times\sqrt[1.2]{\log\left(\frac{R}{2.54}\frac{A}{\ell}\right)} \quad (\text{kV / cm})\ 1.2\mu\text{s} / 50\mu\text{s waveform, in SF}_6 \text{ gas}$$

$$\hat{V} = 4.3\times\sqrt[1.2]{\log\left(\frac{\rho}{2.54}\right)} = 4.3\times\sqrt[1.2]{\log\left(\frac{R}{2.54}\frac{A}{\ell}\right)} \quad (\text{kV / cm})\ 1.2\mu\text{s} / 50\mu\text{s waveform, in air} \tag{25.11}$$

$$\hat{V} = 3.0\times\log\left(\frac{\rho}{2.54}\right) = 3.0\times\left(\frac{R}{2.54}\frac{A}{\ell}\right) \quad (\text{kV / cm})\ 50\mu\text{s} / 1000\mu\text{s waveform, in air}$$

$$\hat{V} = 1.5\times\left(\log\left(\frac{\rho}{2.54}\right)\right)^{\frac{5}{4}} = 1.5\times\left(\log\left(\frac{R}{2.54}\frac{A}{\ell}\right)\right)^{\frac{5}{4}} \quad (\text{kV / cm})\ 100\mu\text{s} / 10000\mu\text{s waveform, in air} \tag{25.12}$$

High resistance values (>100Ω):

For transient impulse voltages across high resistances, the maximum working voltage per cm length is

$$\hat{V} = c\frac{\rho}{A}\times\left(-1+\sqrt{1+\frac{a/\rho\ell}{A}}\right) = bR\times\left(-1+\sqrt{1+a/R}\right) \quad (\text{kV}) \tag{25.13}$$

where *a* and *b* are specified for a given resistance (area and length).

a increases with length and decreases with area

b is independent of length and increases with area

The constant *a* increases and *b* decreases, as the impulse period (time) increases.

25.3.3 Residual capacitance and residual inductance

Generally, all resistors have residual inductance and distributed shunt capacitance. Inductance increases with both resistance and power rating as shown by figure 25.6, while residual capacitance increases mainly with increased pulse rating. For example, a 2 W metal oxide film resistor (typical of film resistors) has ½ pF residual capacitance and inductance varying from 16 nH to 200 nH. A ¼ W family member has 0.13 pF of capacitance and 3 to 9 nH of inductance.

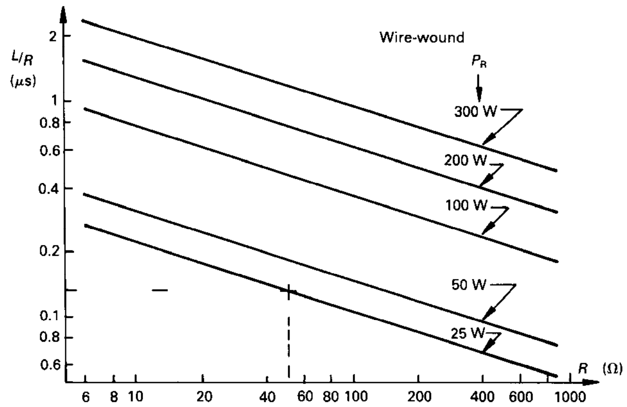


Figure 25.6. *Resistor time constant versus resistance and power rating.*

Film resistors, with resistance above 1 kΩ, having a helical groove, tend to be dominated by interspiral capacitance effects at frequencies above 10 MHz, as seen in figure 25.3a.
Non-inductive elements have low shunt capacitance, such as in the case of carbon composition, while wire-wound resistors can have microhenries of inductance. For example from figure 25.6, a 25 W, 47 Ω, wire-wound resistor may have 6 μH of inductance. Residual inductance increases with resistance and decreases with frequency.
Solid resistive elements, like carbon ceramic, have minimal self-inductance. The method of circuit connection tends to dominate inductance values. Their dielectric constant, ε_r, is about 5, and depends on resistivity.

Example 25.3: ***Coefficients of resistance for a solid carbon ceramic resistor***

Solid carbon ceramic rods of length 1 cm and area 0.25 cm², are used as voltage sharing resistors across each series connected switching device. If the ceramic resistivity is 7500Ω-cm, using equations (25.8) and (25.9), determine

i. the resistance at 25°C, with zero supporting voltage
ii. resistance for a 50°C temperature increase
iii. resistance for a 1000V 20ms voltage pulse
iv. resistance at 50°C and 1000V for 20ms, simultaneously
v. maximum working voltage at (a) 50Hz in air and in SF_6
(b) 10μs/1000μs impulse in air, $a = 2128$ and $b = 0.031$

Solution

i. From equation (25.1), resistance is

$$R = \rho\frac{\ell}{A} = 7500\Omega\text{-cm}\times\frac{1\text{cm}}{0.25\text{cm}^2} = 30\text{k}\Omega$$

ii. Resistance for a 50°C temperature increase is given from equation (25.8)

$$R_{75^\circ C} = R_{25^\circ C}\left(1+\alpha\times\Delta T\right)$$
$$= 30\text{k}\Omega\left(1+\left(1600\times e^{-\log\rho/1.4}-1350\right)\times10^{-6}\times50^\circ\text{C}\right) = 0.9375\times30\text{k}\Omega = 28.12\text{k}\Omega$$

iii. Resistance for a 20ms 1000V pulse is given by equation (25.9)

$$R_{1000\text{V},20\text{ms}} = R_{0\text{V}}\left(1+\phi\times\ell\times V\right)$$
$$= 30\text{k}\Omega\left(1-\left(0.62\times\rho^{0.22}\right)\times10^{-2}\times1\text{cm}\times1000\text{V}\right) = 0.9558\times30\text{k}\Omega = 28.67\text{k}\Omega$$

iv. For both a 50°C temperature increase and a 1000V, 20ms pulse, assume independence and superposition hold, that is, from parts i, ii, and iii

$$R_{75^\circ C,1000V} = R_{25^\circ C}\left(1+\alpha\times\Delta T\right)\left(1+\phi\times\ell\times V\right)$$
$$= 30\text{k}\Omega\times\left(1+\left(1600\times e^{-\log\rho/1.4}-1350\right)\times10^{-6}\times50^\circ\text{C}\right)\times\left(1-\left(0.62\times\rho^{0.22}\right)\times10^{-2}\times1\text{cm}\times1000\text{V}\right)$$
$$= 30\text{k}\Omega\times0.9375\times0.9558 = 26.88\text{k}\Omega$$

v. The maximum working voltage at 50Hz is given by equation (25.10), that is

$$\hat{V} = 1.00\times\left(\frac{\rho}{t}\right)^{0.335}\times\ell = 1.00\times\left(\frac{7500\Omega\text{-cm}}{10\text{ms}}\right)^{0.335}\times1\text{cm} = 9.18\text{ kV in SF}_6\text{ gas}$$

$$\hat{V} = 0.87\times\left(\frac{\rho}{t}\right)^{0.3}\times\ell = 0.87\times\left(\frac{7500\Omega\text{-cm}}{10\text{ms}}\right)^{0.3}\times1\text{cm} = 6.33\text{ kV in air}$$

The maximum working voltage, in air, for a 10μs/1000μs impulse is given by equation (25.13)

$$\hat{V} = bR\times\left(-1+\sqrt{1+a/R}\right)$$
$$= 0.031\times30\text{k}\Omega\times\left(-1+\sqrt{1+2128/30\text{k}\Omega}\right) = 13.7\text{kV}$$

♣

25.4 Thermal properties

The continuous power rating of a resistor, P_R, is based on three factors:

- Maximum surface temperature, in free air, over the usable ambient temperature range, typically from -55°C to well over 100°C.

- Stability of resistance when subjected to a dc cyclic load. Typical power dissipation is limited to give 5 per cent resistance change for 2000 hours continuous operation in a 70°C ambient air temperature.
- Proximity of other heat sources and the flow of cooling air.

The temperature rise of a resistor due to power dissipation is determined by the laws of conduction, convection, and radiation (see Chapter 5). The maximum body external temperature, the hot spot temperature, occurs on the surface - at the middle of the resistor length. As previously considered, any temperature rise will cause a change in resistance, depending on a temperature coefficient; examples are given in table 25.1.
Within the nominal operating temperature range of a resistor, the hot spot temperature, T_h, is given by (similar to equation 5.10)

$$T_h = T_a + R_{\theta_{h-a}}P_d \qquad \text{(K)} \qquad (25.14)$$

The steady state power dissipation is related to temperature rise (°C or K) and the exposed surface area (m²). A solid carbon ceramic resistor yields an excellent model for the relationship between temperature and power since it has a homogeneous composition and uniform cross section. For example, heat loss (power dissipated) by radiation and convection in still 25°C air, is given by

$$P_d = 2.6\times\left(\Delta T\right)^{1.4}\times A_{surface} \qquad \text{(W)} \qquad (25.15)$$

where $\Delta T = T_h - T_a$ and $A_{surface}$ is the exposed radiating surface.

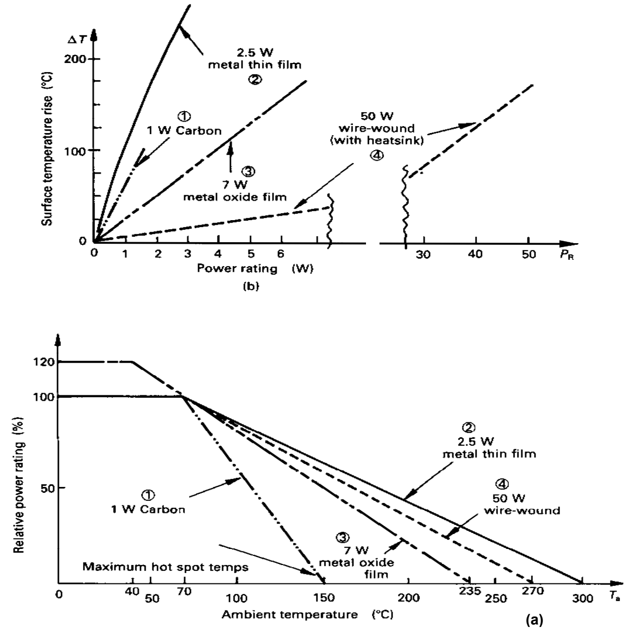


Figure 25.7. *Power resistor thermal properties: (a) power derating with increased temperature and (b) surface temperature increase with increased power dissipation.*

The hot spot temperature is limited, thus as the ambient temperature, T_a, increases the allowable power dissipated decreases, as shown in figure 25.7a for four different elements. These curves show that:

- No power can be dissipated when the ambient temperature reaches the hot spot temperature.
- No derating is necessary below 70°C.
- Some resistors, usually those with higher power ratings, can dissipate higher power at temperatures below 70°C.

The typical linear derating for power and energy of an element in an ambient temperature T_a, can usually be expressed in the form

$$P(T_a) = P_{T\ reference} \times \frac{\hat{T} - T_a}{\hat{T} - T_{T\ reference}} \qquad (25.16)$$

for temperature T_a greater than the reference temperature and $P(\hat{T}) = 0$.

Figure 25.7b shows the resistor surface temperature rise above ambient, nominally 20°C, at different levels of power dissipation. The lead lengths can significantly affect the thermal dissipation properties of resistors and an increase in lead length

- decreases the end of the lead, or soldering spot temperature
- increases the body temperature.

These characteristics are shown for 5 W and 20 W 'cemented' wire-wound resistors in figure 25.8. Figure 25.8a shows how the soldering spot temperature is affected by lead length. Figure 25.8b, on the other hand, is based on the assumption that the soldering spot is represented by an infinite heatsink. Therefore the shorter the lead length, the lower the body temperature for a given power dissipation. It is important to limit the solder pad temperature in order to ensure the solder does not melt – a distinct possibility with continuously dissipating power resistors soldered on pcbs.

25.4.1 Resistors with heatsinking

Aluminium clad resistors suitable for heatsink mounting, as shown in figure 25.1c, are derated with any decrease in the heatsink area from that at which the element is rated. Figure 25.9 shows the derating necessary for a range of heatsink-mounted resistors. For a given heatsink area, further derating is necessary as the ambient temperature increases. Figure 25.7a, curve 4, describes the ambient temperature related power derating of the aluminium-clad resistors on the rated heatsink, characterised in figure 25.9. Figure 25.7a, curve 4, can be used to derate these resistors when operating in an ambient other than 20°C, with the rated heatsink area shown in figure 25.9. The same percentage derating is applicable to a heatsink area smaller than the nominal area.

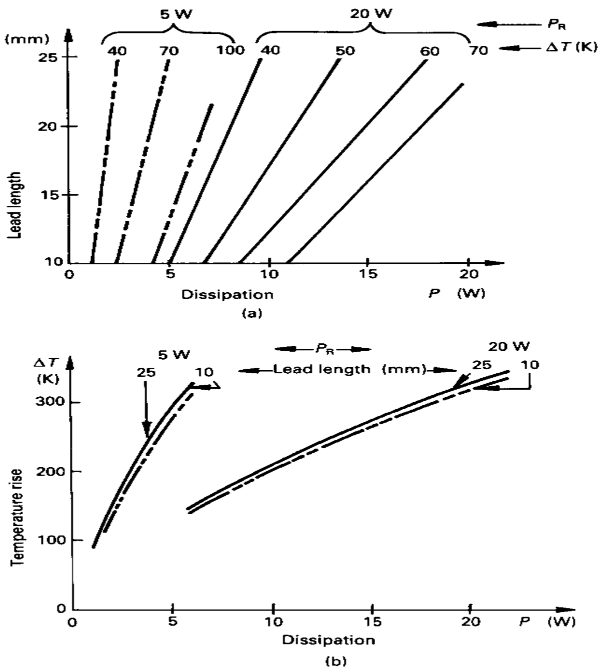


Figure 25.8. *Wire-wound 5 W and 20 W resistor dissipation as a function of: (a) lead length and temperature rise at the end of the lead (soldering spot) and (b) temperature rise of the resistor body, for two lead lengths.*

Example 25.4: ***Derating of a resistor mounted on a heatsink***

What power can be dissipated by an aluminium-clad, wire-wound resistor, (specified in figure 25.9), rated nominally at 50 W, in an ambient of 120°C with a heatsink reduced to 300 cm^2 and 1 mm thick?

Solution

The heatsink area has been reduced to 56 per cent, from 535 to 300 cm^2, hence from figure 25.9 the power rating below 70°C is reduced from 50W to 37.5 W.
From figure 25.7a, curve 4, at 120°C ambient, derating to 75 per cent of the relevant power rating is necessary. That is, 75 per cent of 37.5 W, 28.1 W, can be dissipated at an ambient of 120°C and with a heatsink area of 300 cm^2.

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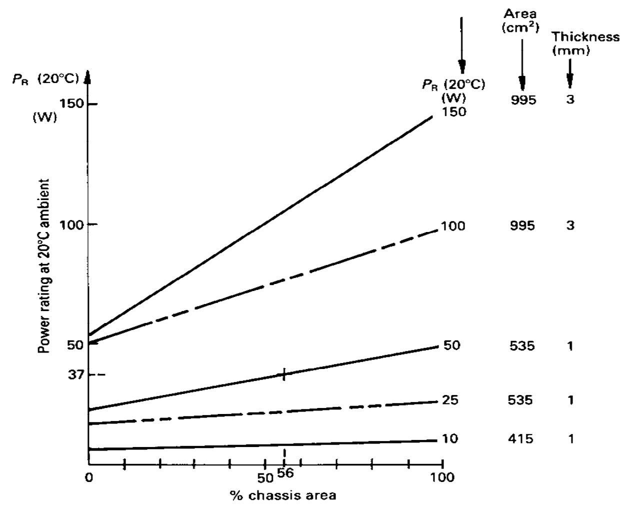

Figure 25.9. *Power dissipation of resistors mounted on a smaller heat sink than specified, right.*

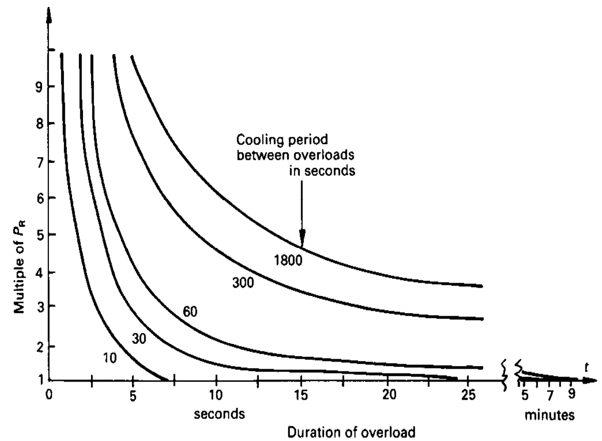

Figure 25.10. *Permissible short time overload ratings for heavy-duty tape wound power resistors.*

25.4.2 Short time or overload ratings

Resistors with power ratings greater than a watt are designed to handle short-term overloads, either continuously for minutes, or repetitively in short bursts of a few seconds. Figure 25.10 can be used to determine allowable short-duration, repetitive pulses. It can be seen that high, short-duration power pulses of a few seconds can be handled if the repetition rate is low. As the pulse duration increases, the overload capability reduces rapidly, with minimal overload allowable with power pulses over a few minutes in duration.

For power pulses of less than 100 ms, the power is absorbed by the thermal capacity of the resistive element and little heat is lost to the surroundings. The temperature rise ΔT of the resistive element in this adiabatic condition is given by (equation 5.2)

$$\Delta T = \frac{W}{mc} \qquad \text{(K)} \qquad (25.17)$$

where c is the specific heat capacity of the resistive element (J/kg/K)
W is the energy in the pulse of time t_p, (J)
m is the mass of the resistive element (kg).

Due to its homogeneous composition, the carbon ceramic rod resistor yields a good model for the relationship for temperature rise (°C) in free air due to an energy injection pulse. Using the data in appendix 25.8:

$$\Delta T = \frac{W}{mc} = \frac{W}{\gamma \times volume \times c}$$

$$= \frac{W}{2250 \times \left(\frac{\pi D^2}{4} \times \ell\right) \times 8.89 \times 10^3} = \frac{W}{1.57 \times 10^6 \times D^2 \times \ell} \qquad \text{(K)} \qquad (25.18)$$

where the effective mass is calculated from the density, γ, and the active volume (all SI units).

Example 25.5: ***Non-repetitive pulse rating***

A 100 A rms, sine pulse with a period of 50 ms is conducted by a wire-wound resistor, constructed of 1 mm^2 cross-section *Ni-Cr* alloy (Nichrome).
Calculate the temperature rise. Assume for *Ni-Cr*

resistivity $\rho = 1 \times 10^{-6}\ \Omega$ m
specific heat $c = 500$ J/kg/K
density $\gamma = 8000$ kg/m^3

Solution

The mass m of the element of length ℓ and area A is given by

$$m = \gamma \ell A \qquad \text{(kg)}$$

Resistance R of the wire is given by

$$R = \rho \frac{\ell}{A} \qquad (\Omega)$$

The pulse energy is given by

$$W = \int_o^{t_p} i^2 R\, dt = \int_o^{50\text{ms}} \left(\sqrt{2} \times 100 \sin(\omega t)\right)^2 R\, dt$$
$$= 500R \qquad \text{(J)}$$

Substitution for R yields

$$W = 500 \times \rho \frac{\ell}{A} \qquad \text{(J)}$$

The temperature rise ΔT from equation (25.17) is given by

$$\Delta T = \frac{W}{mc} = 500 \times \frac{\rho \ell}{A} \times \frac{1}{c} \times \frac{1}{\gamma \ell A}$$
$$= \frac{500\rho}{\gamma c A^2} = \frac{500 \times 1 \times 10^{-6}}{8000 \times 500 \times \left(1 \times 10^{-6}\right)^2} = 125\text{K}$$

♣

25.5 Repetitive pulsed power resistor behaviour

A resistor may be used in an application where the power pulse experienced at a repetition rate of kilohertz is well beyond its power rating, yet the average power dissipated may be within the rated

power. The allowable square power pulse $\hat{P}$, of duration t_p and repetition time T, can be determined from figure 25.11a, which is typical for power film resistors, at a 70°C ambient. Within these bounds, any resistance change will be within the limits allowable at the continuous power rating. The pulse duration t_p, restricts the maximum allowable pulse voltage $\hat{V}$, impressed across a film resistor, as shown in figure 25.11b.

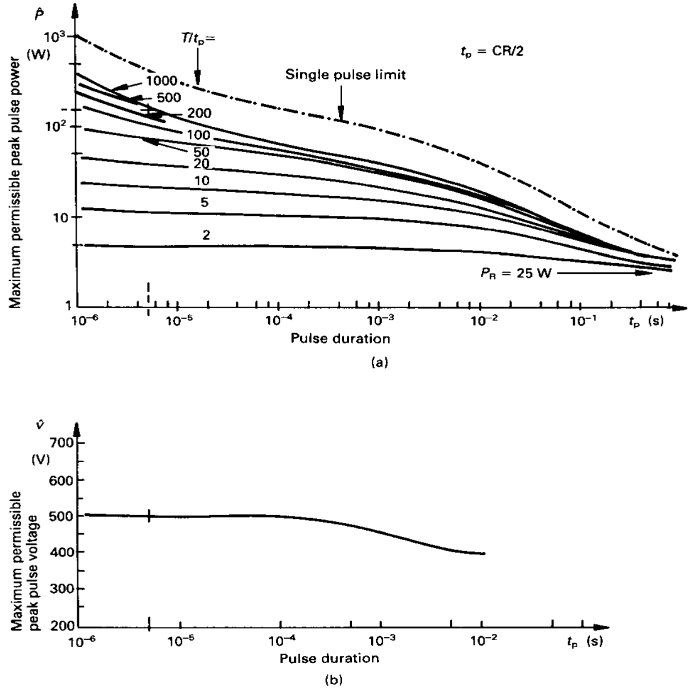

Figure 25.11. *Pulsed capabilities of a power metal film resistor, 2.5 W: (a) maximum permissible peak pulse power versus pulse duration and (b) maximum permissible peak pulse voltage versus pulse duration.*

Example 25.6: ***Pulsed power resistor design***

A 1 kΩ-10 nF, *R-C* snubber is used across a MOSFET which applies 340 V dc across a load at a switching frequency of 250 Hz. Determine the power resistor requirements.

Solution

The average power dissipated (charging plus discharging) in the resistor, which is independent of resistance, is:

$$\overline{P} = CV^2 f = (10 \times 10^{-9}) \times 340^2 \times 250\text{Hz} = 0.29\text{ W}$$

Figure 25.11 is applicable to a 2.5 W metal film resistor, when subjected to rectangular power pulses. The peak power $\hat{P}$ occurs at switching at the beginning of an *R-C* charging or discharging cycle.

$$\hat{P} = V_i^2 / R = (340\text{V})^2 / 1000\Omega = 116\text{ W}$$

where V_i, 340 V, is the maximum voltage experienced across the resistor. The 2.5W element has a power rating greater than the average to be dissipated, 0.29W. Assuming exponential pulses, then

$$t_p = \tfrac{1}{2}\tau = \tfrac{1}{2}CR = \tfrac{1}{2} \times 10 \times 10^{-9} \times 10^3 = 5\mu\text{s}$$

The average pulse repetition time, T, is 2 ms, therefore $T / t_p = 400$. From Figure 25.11, the peak allowable power is 150 W while the limiting voltage is 500 V. Both the experienced voltage, 340 V, and power, 116 W, are within the allowable limits. The proposed 2.5 W, 1 kΩ, metal thin film power resistor is suitable. Furthermore from figure 25.7, curve 2, with an average power dissipation of 0.29 W, that is 11.6 per cent of P_R, the maximum allowable ambient temperature is 213°C, while the hot spot temperature is 40°C above ambient for an ambient below 70°C. In terms of average power dissipated, this resistive element is lightly stressed. On the other hand, the transient stress is relatively high.

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25.5.1 Empirical pulse power model

An empirical formula for the maximum pulse power may be given in the case of a metal film resistor. Typically, for a 1 W @ 70°C, 700 V rated, 60 K/W, metal film resistor

$$\hat{P} \le \sqrt{\frac{15}{t_p}} \qquad \text{(W)} \qquad (25.19)$$

where 1 μs ≤ t_p ≤ 100 ms, such that the average dissipation is less than the rated dissipation.
Using t_p = 5 μs from example 25.2 in equation (25.19) indicates that this 1 W resistor is suitable for the application considered in example 25.4. In fact a ⅓W, 600 V rated, metal film resistor can fulfil the snubber function when using a quoted $\hat{P} = \sqrt{5/t_p}$.

25.5.2 Mathematical pulse power models

A more rigorous mathematical approach to power dissipation is possible for carbon ceramic resistive elements because of the symmetrical shapes and homogeneous composition. The thermal time constant in free air at 25°C is defined by the ratio of the maximum rated energy $\widehat{W}$ to maximum rated power $\hat{P}$, that is

$$\tau = \frac{\widehat{W}}{\hat{P}} \qquad (25.20)$$

The temperature rise for a single energy pulse is given by equation (25.17), that is

$$\Delta T = \frac{W}{mc} \qquad \text{(K)}$$

If the temperature coefficient of resistance is assumed constant, then the peak temperature rise ΔT_p for n repetitive pulses of energy W and of period t, is

$$\Delta T_p = \Delta T \times \left[\left(1 - \left(e^{-\frac{t}{\tau}} \right)^n \right) + \left(1 - e^{-\frac{t}{\tau}} \right) \right] \qquad (25.21)$$

where ΔT is the temperature rise associated with each electrical pulse.
For continuous pulses, this equation asymptotes to

$$\Delta T_p = \Delta T \left[1 + \left(1 - e^{-\frac{t}{\tau}} \right) \right] \qquad (25.22)$$

Example 25.7: *Solid carbon ceramic resistor power rating*

The resistor in example 25.3 has a maximum power rating of 4W at 25°C and a maximum energy rating of 1200J at 25°C. The element is subject to 2½ms, 1J energy pulses at a 20ms repetition rate. Determine

i. the thermal time constant
ii. the maximum power and energy limits at 100°C, if the resistor is linearly derated to zero at 200°C, from its rating at 25°C. What is the new thermal time constant?
iii. the temperature rise due to
- one energy pulse
- after 1 second of pulses
- continuous pulses

Solution

i. The thermal time constant at 25°C is defined by equation (25.20)

$$\tau = \frac{\widehat{W}_{25^\circ C}}{\hat{P}_{25^\circ C}} = \frac{1200\text{J}}{4\text{W}} = 300\text{ s}$$

ii. The power derating is given by

$$P(T) = P_{25^\circ C} \times \left(\frac{200°C - T}{200°C - 25°C} \right)$$

$$P(100°C) = 4W \times \left(\frac{200°C - 100°C}{175°C} \right) = 2.28W$$

Similarly, the energy derating is given by

$$W(T) = W_{25^\circ C} \times \left(\frac{200°C - T}{175°C} \right)$$

$$W(100°C) = 1200J \times \left(\frac{200°C - 100°C}{175°C} \right) = 686J$$

The thermal time constant remains unchanged after the two linear transformations

$$\tau = \frac{\widehat{W}_{100^\circ C}}{\hat{P}_{100^\circ C}} = \frac{686J}{2.28W} = 300\text{ s}$$

iii. The temperature rise due to one energy pulse (20ms repetition rate) is given by equation

$$\Delta T = \frac{W}{mc} = \frac{W}{1.57 \times 10^6 \times D^2 \times \ell} \qquad \text{(K)}$$

$$= \frac{1J}{1.57 \times 10^6 \times \frac{4}{\pi} \times 0.25 \times 10^{-4} \times 1 \times 10^{-2}} = 2°C$$

From equation (25.21) after 1 second, that is 50 pulses

$$\Delta T_{p-2} = \Delta T \times \left[\left(1 - \left(e^{-\frac{t}{\tau}} \right)^n \right) + \left(1 - e^{-\frac{t}{\tau}} \right) \right]$$

$$= 2°C \times \left[\left(1 - \left(e^{-\frac{20ms}{300s}} \right)^{50} \right) + \left(1 - e^{-\frac{20ms}{300s}} \right) \right] = 2°C \times \left[0.003328 + 0.0000666 \right] = 0.0007°C$$

In steady state, from equation (25.21), the peak temperature rise is

$$\Delta T_p = \Delta T \times \left[1 + \left(1 - e^{-\frac{t}{\tau}} \right) \right]$$

$$= 2°C \times \left[1 + \left(1 - e^{-\frac{20ms}{300s}} \right) \right] = 2°C \times \left[1 + 0.0000666 \right] = 2.0°C$$

♣

All resistors are thermally derated, starting at about 70°C, linearly to zero power dissipation at a maximum operating temperature, which is shown in Table 25.5 for the various resistor types.

Table 25.2: Zero rated power for thermally derated resistor types

Type (derating usually starts at 70°C)	Maximum temperature °C
Wire wound - power alumina former/ power beryllia former / precision	275 / 350 / 175
Metal foil	125
Metal foil – power / precision	170 / 175
Nickel film	150
Tantalum nitride film	150
Cermet thin film	200
Metal oxide film	125
Carbon film – power / precision	100 / 120
Metal glazed – power / precision	200 / 200
Thick film - metal oxide / metal oxide power	150 / 275
Conducting plastic – power / precision	120 / 120
Carbon composition / ceramic	130 / 220

25.6 Stability and endurance

The resistance stability of a resistor is dependent on power dissipation, ambient temperature, and resistance value. An endurance test gives the worst-case variation in resistance value or stability. It is the percentage resistance change at rated power and hot spot temperature after a specified time. An endurance specification is of the form:

- 1000 hours at recommended maximum dissipation P_R,
- which will limit the hot spot temperature to 375°C:
- ΔR less than 5 per cent of R

The time, percentage change in R, and temperature are varied with resistor type and physical size.

At power levels below rated dissipation, better stability than that for the endurance test is attainable, for the same duration. The stability period can be extended by the following empirical formula

$$\left.\frac{\Delta R}{R}\right|_{t} \approx X^{\log\frac{t}{t_1}} \times \left.\frac{\Delta R}{R}\right|_{t_1} \qquad (25.23)$$

which is valid for $10^{-3} \le t \le 10^5$ hours. The base χ depends on the resistor type and is between 1.1 and 5.

Performance monograms as shown in figure 25.12 may be provided to enable a given resistor to be used at dissipation levels which will result in the stability required for that application. The first quadrant in figure 25.12 satisfies the thermal equation (25.14), while the third quadrant satisfies equation (25.19), with χ = 3.17. The following example illustrates many of the features of the stability performance monogram of figure 25.12.

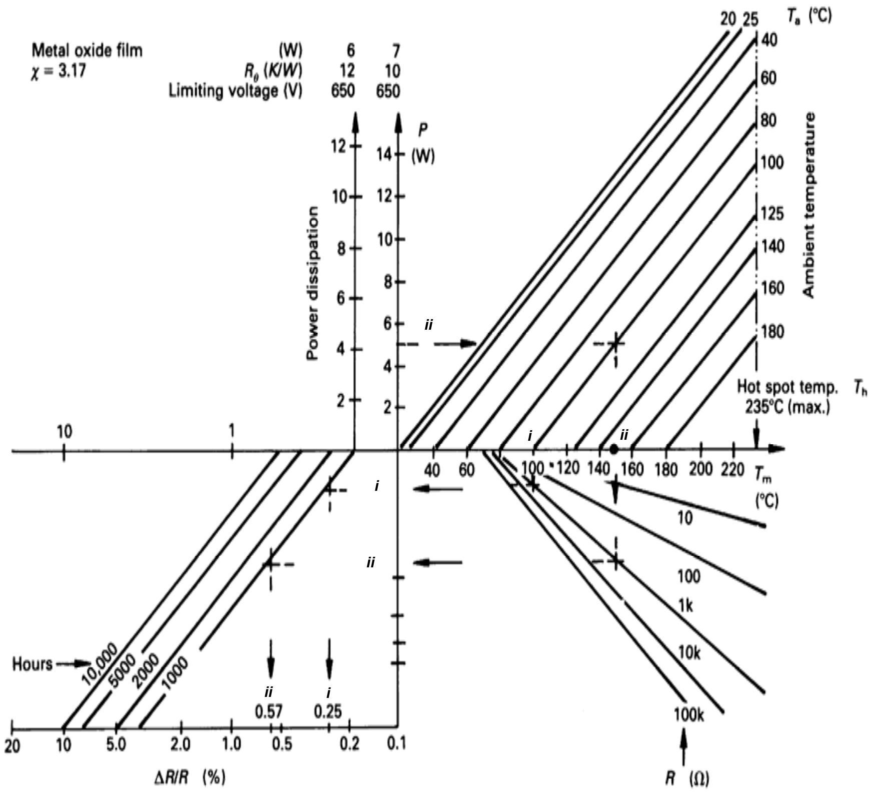

Figure 25.12. *Performance monogram for power resistors, showing the relationship between power dissipation, ambient temperature, hot spot temperature, and maximum resistance drift in time.*

Example 25.8: *Power resistor stability*

A 1 kΩ, 7 W, power metal oxide film resistor dissipates 5 W. If the maximum ambient is 100°C, use the monograph in figure 25.12 to find

i. the stability at 100°C while in circuit for 1000 hours but in a standby mode, that is, P = 0 W
ii. the hot spot temperature when dissipating 5 W
iii. the maximum expected resistance drift after 10^3 and 10^5 hours
iv. lifetime (5% = $\Delta R/R$) dissipating 5W in a 60°C ambient.

Solution

i. The resistance change given from the monogram for P = 0W at a 100°C ambient is indicative of the shelf-life stability of the resistor when stored in a 100°C ambient.
The stability is determined by performing the following operations. Find the intersection of P = 0 and the diagonal for T_a = 100°C. Then project perpendicularly to the 1kΩ diagonal. The intersection is projected horizontally to the 1000 hour diagonal. This intersection is projected perpendicularly to the stability axis.
For example, from projections on figure 25.12, after 1000 hours, in a 100°C ambient, a 0.25 per cent change is predicted. For the 1kΩ resistor there is a 95 per cent probability that after 1000 hours the actual change will be less than 2.5 Ω (0.25% of 1kΩ).

ii. The 5W load line is shown in figure 25.12. A hot spot temperature, T_m, of 150°C is predicted (100°C + 5 W × 10°C/W).

iii. With a 1kΩ resistor after 1000 hours, a $\Delta R/R$ of 0.57 per cent is predicted, as shown on figure 25.12. There is a 95 % probability that the actual change will be less than 5.7Ω.
The monogram does not show stability lines beyond 10,000 hours. Equation (25.23), with χ=3.17, can be used to predict stability at 100,000 hours

$$\left.\frac{\Delta R}{R}\right|_{10^5} \approx 3.17^{\log\frac{10^5}{10^3}} \times 0.57\% = 18.25\%$$

After 100,000 hours, it is 95 per cent probable that the actual resistance change of the 1 kΩ resistor will be less than 182.5 Ω (18¼% of 1kΩ).

iv. From the first quadrant in figure 25.12, the hot spot temperature is 110°C when dissipating 5W in a 60°C ambient. Solving equation (25.23) for 5% = $\Delta R/R$ = 5%:

$$\left.\frac{\Delta R}{R}\right|_{10^x} = 3.17^{\log\frac{10^x}{10^3}} \times 0.05$$

gives x = 5. That is, there is a 95% probability that the resistor will survive 10^5 hours with a resistance variation of less that 5%.

♣

25.7 Special function power resistors

Film and wire-wound resistors are available which have properties allowing them to perform the following functions

- fusing
- circuit breaking
- temperature sensing
- current sensing.

Table 25.3: Fusible resistor characteristics

parameter		condition	units	Metal alloy film	Wire wound
Power	P_R	@ 70°C	W	0.25 - 4.5	1 - 2
Resistance range	R		Ω	0.22 - 10k	0.1 - 1k
Tolerance			%	2	5
Temperature coefficient (resistance dependent)	α	x 10^{-6}	/K	± 500	-400 to + 1000
Stability		@ P_R T_a = 70°C, 1000 hours	%	2	10
Working voltage	V_m		V	$\sqrt{P_R R}$	$\sqrt{P_R R}$

25.7.1 Fusible resistors

Resistors up to 2 W are available which fuse when subjected to an overload current. The resistive element fused is generally metal alloy film, although only wire-wound elements are suitable at low resistance levels. The power load and interruption time characteristic shown in figure 25.13a shows that rated power can be dissipated indefinitely, while as the power increases significantly above the rated dissipation, the interruption time decreases rapidly. Interruption generally means that the nominal resistance has increased at least 10 times. Irreversible resistance changes can be caused by overloads which raise the change in hot spot temperature beyond 150°C, for the elements illustrated by figure 25.13b. The nature of the resistive element makes it unsuitable for repetitive power pulse applications.
Typical fusible resistors are summarised in table 25.3.

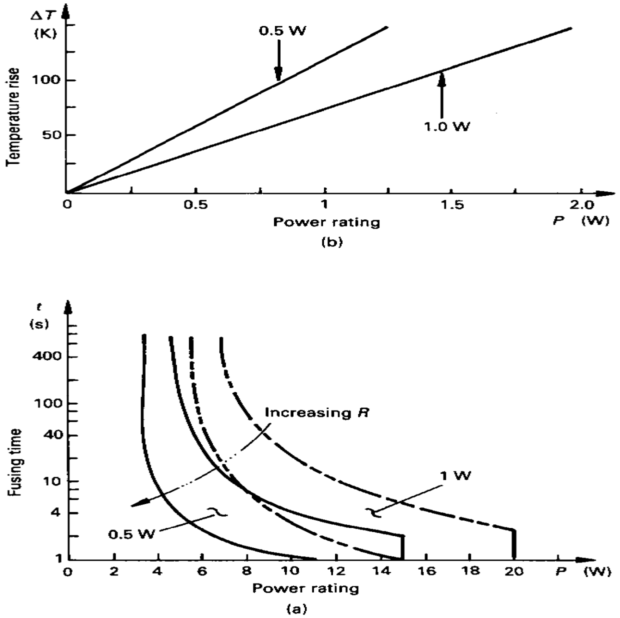

Figure 25.13. *Fusible resistor characteristics:*
(a) time to interruption (10 x R_R) as a function of overload power and
(b) temperature rise above ambient as a function of power dissipated.

25.7.2 Circuit breaker resistors

The construction of two types of wire-wound circuit breaker resistors is shown in figure 25.14. Under overload conditions the solder joint melts, producing an open circuit. After fusing, the solder joint can be resoldered with lead free solder.

The joint melts at a specified temperature, and to ensure reliable operation the solder joint should not normally exceed 150°C. This allowable temperature rise is shown in figure 25.15a, while the circuit breaking time and load characteristics for both constructions are shown in figure 25.15b. This characteristic is similar to that of fusible resistors. A typical power range is 1 to 6 W at 70°C, with a resistance range of 75mΩ to 82kΩ and temperature coefficient of -80 to +500 × 10^{-6}/K depending on the resistance values. The maximum continuous rms working voltage tends to be limited by the power, P_R, according to $\sqrt{P_R R}$.

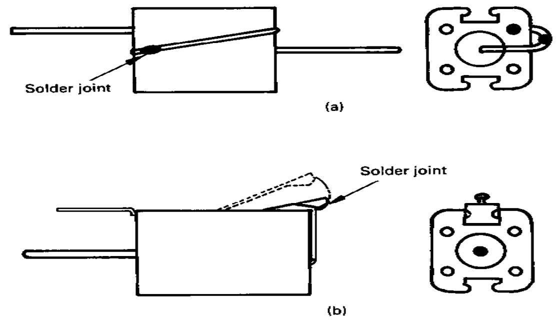

Figure 25.14. *Two circuit breaker resistors construction: (a) type 1 and (b) type 2.*

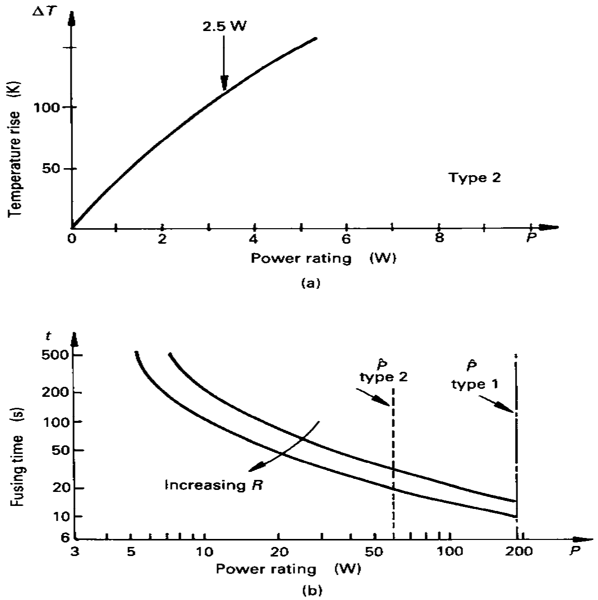

Figure 25.15. *Circuit breaker characteristics: (a) solder joint temperature rise versus power dissipated for resistor type 2 and (b) fusing times versus load for resistor types 1 and 2.*

25.7.3 Temperature sensing resistors

The temperature dependence of a resistive element can be exploited to measure temperature indirectly. Unlike normal resistors, temperature-sensing resistors require a large temperature coefficient to increase resistance variation sensitivity with temperature.
Both metal film and wire-wound temperature sensing elements are available with a temperature coefficient of over +5000 × 10^{-6}/K with 1 per cent linearity over the typical operating range of -55°C to 175°C. The high temperature sensitivity gives a 57 per cent increase in resistance between 25°C and 125°C.
The low power elements, up to ¼W @ 70°C, tend to be metal oxide, with a typical resistance range at 25°C of 10Ω to 10kΩ. A conformal encapsulation is used to minimise thermal resistance, hence ensuring an extremely fast response. For example, a 1/20 W temperature sensing resistor can have a thermal time constant to a step temperature, in still air, of 3.7 s. This time constant increases to 31 s for a larger mass, ¼ W rated resistor.

At powers commencing at 1 W, wire-wound elements are employed which utilise positive temperature coefficient alloy resistance wire. The nominal resistance range is lower than the film types; typically from 0.1 Ω to 300 Ω at 25°C. Response is slower than film types, but can be improved if oil immersed.
Glazed thick film temperature sensing resistors can be used to provide a negative temperature coefficient, -3000 × 10^{-6}/K at 25°C. Power is limited to ¼ W with a dissipation constant of up to 8.1 mW/K at 25°C in still air. Low thermal time constants of only 2.9 s are possible with 1/20 W elements.

The allowable working voltage for all types is power limited, $V=\sqrt{P_R R}$.

25.7.4 Current sense resistors

The resistive element consists of a flat metal band, with spot-welded terminals, and a ceramic encapsulation. The flat-band construction results in a non-inductive resistor of both high stability and overload capacity. Low current third and fourth terminal voltage sensing (Kelvin) leads may be incorporated; alternatively a mΩ/cm correction factor for lead length is given.
Power ratings of up to 20 W at 70°C and 20 A maximum, with a resistance range of 10mΩ to 10Ω are available. At these low resistance levels, the maximum continuous working voltage is power limited. The resistance temperature coefficient is typical of a wire-wound resistor, 100 to 600 × 10^{-6}/K depending on the resistance level.

25.7.5 Thermistors

A *thermistor* is a type of resistor with resistance varying predictably and rapidly according to its temperature. The word is a portmanteau of thermal and resistor.
Thermistors are widely used as inrush current limiters, temperature sensors, self-resetting over-current protectors, and self-regulating heating elements.
The resistance of a thermistor is solely a function of its absolute body temperature. When testing for resistance accuracy it is essential that the surrounding environmental temperature is held constant, and power dissipated in the thermistor is low enough to insure no 'self-heating'.
With transition metals, the relationship between resistance and temperature is linear, first-order, that is:

$$\Delta R = k \Delta T \qquad (25.24)$$

where:

- ΔR = change in resistance
- ΔT = change in temperature
- k = first-order temperature coefficient of resistance

If k is positive, the resistance increases with increasing temperature, and the metal is termed a positive temperature coefficient (PTC) material. If k is negative, as with some sintered compounds, the resistance decreases with increasing temperature, and the compound is termed a negative temperature coefficient (NTC) material.
Thermistors can be classified into two types depending on the sign of k, namely NTC and PTC thermistors. Resistors that are not thermistors are designed to have a k as close to zero as possible, so that their resistance remains near constant over a wide temperature range.

NTC thermistors are made from chemically stabilised metallic oxides (such as manganese, iron, cobalt, nickel, copper and zinc), compressed and sintered at high temperatures between 1000°C and 1400°C to produce the polycrystalline NTC thermistor, which at a finally stage of manufacture is aged for stability.

Most PTC thermistors are of the 'switching' type, which means that their resistance rises suddenly at a certain critical temperature. The devices are made of a doped polycrystalline ceramic containing barium titanate ($BaTiO_3$) and other compounds. The dielectric constant of this ferroelectric material varies with temperature. Below the Curie point temperature, the high dielectric constant prevents the formation of potential barriers between the crystal grains, leading to a low resistance. In this region the device has a small negative temperature coefficient. At the Curie point temperature, the dielectric constant drops sufficiently to allow the formation of potential barriers at the grain boundaries, and the resistance increases sharply. At even higher temperatures, the material reverts to NTC behaviour.
Another type of PTC thermistor is the polymer PTC. This consists of a slice of plastic with embedded carbon grains. When the plastic is cool, the carbon grains are all in contact with each other, forming a conductive path through the device. When the plastic heats up, it expands, forcing the carbon grains apart, and causing the resistance of the device to rise rapidly. Like the $BaTiO_3$ thermistor, this device has a highly nonlinear resistance/temperature response and is used for switching, not for proportional temperature measurement.

Another type of thermistor is a Silistor - a thermally sensitive silicon resistor. Silistors are similarly constructed and operate on the same principles as other thermistors, but employ silicon as the semiconductive component material. Over small changes in temperature, if the right semiconductor is used, the resistance of the material is linearly proportional to the temperature. There are many different semiconducting thermistors with a range from 0.01 degree Kelvin to 2,000 K; -273.14°C to 1,700°C).

The NTC thermistor is best suited for precision temperature measurement. The PTC thermistor is best suited for temperature compensation and current limiting, as considered, in detail, in chapter 10.3.2.

Negative temperature coefficient (NTC) thermistors

In practice, the linear approximation in equation (25.24) is only applicable over a small temperature range. For accurate temperature measurements, the resistance/temperature curve of the device is described in more detail using the Steinhart-Hart third-order approximation equation:

$$\frac{1}{T} = a + b\ln R + c\ln^3 R$$

where *a*, *b* and *c* are called the Steinhart-Hart parameters, and must be specified for each device. *T* is the temperature in degree Kelvin and *R* is the resistance in Ohms. To give resistance as a function of temperature, the above equation can be rearranged into:

$$R = e^{(\beta - ½\alpha)^{\frac{1}{3}} - (\beta - ½\alpha)^{\frac{1}{3}}}$$

where

$$\alpha = \frac{a - \frac{1}{T}}{c} \text{ and } \beta = \left(\left(\frac{b}{3c}\right)^3 + ¼\alpha^2\right)^{½}$$

The error in the Steinhart-Hart equation is generally less than 0.02°C in the measurement of temperature. As an example, typical values for a thermistor with a resistance of 3kΩ at room temperature (25°C = 298.15 K) are:

$$a = 1.40 \times 10^{-3}$$
$$b = 2.37 \times 10^{-3} = \ell nR_1 - \ell nR_3 \,/\, \tfrac{1}{T_1} - \tfrac{1}{T_2}$$
$$c = 9.90 \times 10^{-8} = P_{T2-T1} \,/\, T_2 - T_1$$

Temperature coefficients valid over a small temperature range.

i. NTC thermistors can also be characterised with the *B* parameter equation, which is essentially the Steinhart Hart equation with $c = 0$.

$$\frac{1}{T} = \frac{1}{T_o} + \frac{1}{B}\ln\frac{R}{R_o} \qquad \left(\text{or } T = \left(\frac{1}{B}\ln\left(\frac{R}{R_o}\right) + \frac{1}{T_o}\right)^{-1} \qquad (\text{K})\right)$$

where the temperatures are in degree Kelvin. Rearranging yields:

$$R = R_o e^{B\left(\frac{1}{T} - \frac{1}{T_o}\right)} \qquad (25.25)$$

R_o and T_o are rated temperature and resistance at that temperature (usually 25°C=298.15K), or

$$B = \frac{T\,T_o}{T_o - T}\ln\frac{R}{R_o} = \frac{T\,T_o}{T_o - T} \times 2.3026 \times \log_{10}\frac{R}{R_o}$$

The *B*-parameter equation can also be arranged in the form $y = mx + c$ by taking natural logs of both sides of the equation to give $\ell nR = Bx + 1 / T$. This can be used to convert the function of resistance against temperature of a thermistor, into a linear function in which the gradient can be found to give the *B* value (typically 2500K to 5000K). A quadratic approximation for *B* can be highly accurate, where

$$B = a + bT + cT^2$$

The quadratic coefficients are device material dependant, typically 2000 < *a* < 4000, 1 < *b* < 8, and -0.0001 < *c* <-0.01.

ii. Also, in conjunction with equation (25.25), the temperature coefficient of resistance or alpha, α, of an NTC thermistor is defined as:

$$\alpha = \frac{1}{R}\frac{dR}{dT} = -\frac{B}{T^2}$$

Conduction model

Many NTC thermistors are made from a pressed disc or cast chip of a semiconductor such as a sintered metal oxide. They work because raising the temperature of a semiconductor increases the number of electrons able to move about and carry charge - it promotes them into the conduction band. The more charge carriers that are available, the more current a material can conduct. This is described by the formula:

$$I = qnAv \qquad (25.26)$$

I = electric current (ampere)
n = density of charge carriers (count/m³)
A = cross-sectional area of the material (m²)
v = velocity of charge carriers (m/s)
q = charge of an electron $q = 1.602\times10^{-19}$ coulomb

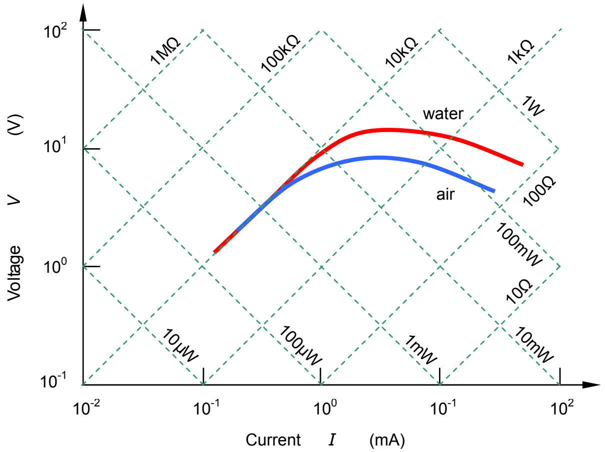

Figure 25.16. *I-V characteristics of a 10kΩ NTC thermistor at 25°C.*

The NTC thermistor has three regions

- The straight line section is for negligible self heating, thus V and I are proportional, whence the resistance is determined only by the temperature. This is the temperature sensing region with $dV/dI = R$ = constant
- The non-linear rise and drop is due to self heating. At maximum voltage the relative decrease in resistance $\Delta R/R$ resulting from self-heating is equal to the relative increase in current, $\Delta I/I$, implying $dV/dI = 0$.
- The falling edge is when the decrease in resistance is greater than the relative increase in current. This self heating region is used for current inrush control and liquid level sensing, that is when $dV/dI < 0$.

Self-heating effects

Though commonly used, 'self-heating' is a misnomer. Thermistors are passive devices and thus cannot heat themselves. It is the external circuit that supplies the energy that causes the heating. 'Resistive heating' or Joule heating are more accurate terms.

When a current flows through a thermistor, it generates heat which raises the temperature of the thermistor above that of its environment. If the thermistor is being used to measure the temperature of the environment, this electrical heating may introduce a significant error if a correction is not made.

The electrical power input to the thermistor is

$$\frac{dH}{dt} = P_e = IV = I^2R = U\left(T - T_A\right) + C_{th}\frac{dT}{dt}$$

where I is current and V is the voltage drop across the thermistor.
dH/dt is the change of stored thermal energy with time
U is the dissipation factor of the thermistor = dP/dT, $U = h\times A = 1/R_\theta$, W/K
T is the instantaneous NTC temperature

T_A ambient temperature
C_{th} heat capacity of the NTC thermistor = $\Delta H/\Delta T = U\times\tau_c$
dT/dt change of temperature with time

The solution to the thermal differential equation is

$$\Delta T = T - T_A = \frac{P_e}{U}\left(1 - e^{-\frac{t}{\tau_c}}\right) \quad \text{where} \quad \tau_c = \frac{C_{th}}{U} = \frac{C_{th}}{h\times A}$$

where τ_c is the thermal cooling time constant (63.2% decrease in temperature time, in still air at 25°C), from 85°C to 47.1°C. The thermal time constant τ_a is time it takes for an unload thermistor to increase its body temperature from 25°C to 62.9°C in a fluid, typically water, at 85°C.

This power is converted to heat, and this heat energy is transferred to the surrounding environment. At thermal equilibrium, when $dT/dt = 0$ or $t >> \tau_c$, the rate of transfer is described by Newton's law of cooling:

$$P_T = U\times\left(T\left(R\right) - T_o\right) = U\,\Delta T$$

where $T(R)$ is the temperature of the thermistor as a function of its resistance R, T_o is the temperature of the surroundings, and δ is the dissipation constant, usually expressed in units of milliwatts per °C. At equilibrium, the two rates must be equal.

$$P_T\left(= U\,\Delta T\right) = P_e\left(= I^2R\right)$$

The current and voltage across the thermistor will depend on the particular circuit configuration. As a simple example, if the voltage across the thermistor is held fixed, then by Ohm's Law we have $I = V/R$ and the equilibrium equation can be solved for the ambient temperature as a function of the measured resistance of the thermistor:

$$T_o = T\left(R\right) - \frac{V^2}{U\times R}$$

or

$$I = \left(\frac{U\times\Delta T}{R\left(T\right)}\right)^{1/2} \quad \text{and} \quad V = \left(U\times\Delta T\times R\left(T\right)\right)^{1/2}$$

The dissipation constant is a measure of the thermal connection of the thermistor to its surroundings. It is generally given for the thermistor in still air, and in well-stirred oil. Typical values for a small glass bead thermistor are 1.5mW/°C in still air and 6.0mW/°C in stirred oil. If the temperature of the environment is known beforehand, then a thermistor may be used to measure the value of the dissipation constant. For example, the thermistor may be used as a flow rate sensor, since the dissipation constant increases with the rate of flow of a fluid past the thermistor.

The NTC thermistor is used in three different modes which services a variety of applications.

i. Resistance versus Temperature Mode - the usual. These circuits perform precision temperature measurement, control and compensation. Unlike the other applications this method depends on the thermistor being operated in a 'zero-power' condition. This condition implies that there is no self-heating. The resistance across the sensor is relatively high in compensation to an RTD element, which is usually in the hundreds of ohms range. Typically, the 25°C rating for thermistors is from 10Ω to 10,000,000 Ω. The housing of the thermistor varies as the requirements for a hermetic seal and ruggedness, but in most cases, there are only two wires connecting the element. This is possible because of the resistance of the wire over temperature is considerably lower than the thermistor element. And typically does not require compensation because of the overall resistance.

ii. Current-Over-Time Mode – This depends on the dissipation constant of the thermistor package as well as element's heat capacity. As current is applied to a thermistor, the package will begin to self-heat. If the current is continuous, the resistance of the thermistor will start to lessen. The thermistor current-time characteristics can be used to slow down the affects of a high voltage spike, which could be for a short duration. In this manner, the thermistor time delay is used to prevent false triggering of relays.

This type of time response is relatively fast as compared to diodes or silicon based temperature sensors. In contrast, thermocouples and RTD's are equally as fast as the thermistor, but do not have the equivalent high level outputs.

iii. Voltage versus Current Mode - Voltage-versus-current applications use one or more thermistors that are operated in a self-heated condition. An example would be a flow meter. The thermistor is in an ambient self-heated condition. The thermistor's resistance is changed by the amount of heat generated by the power dissipated by the element. Any change in the media (gas/liquid) across the device changes the power dissipation factor of the thermistor. The small size of the thermistor allows for this type of application to be implemented with minimal interference to the system.

Aging affects on thermistor stability

'Thermometric drift', the main cause for NTC thermistor drift, is fixed temperature drift at all temperatures of exposure. For example, a thermistor that exhibits a -0.02°C shift at 0°, 40° and 70°C (even though this is a different percentage change in resistance in each case) would be exhibiting thermometric drift. Thermometric drift:

(1) occurs over time at varying rates, based on thermistor type and exposure temperature, and
(2) generally, increases as the exposure temperature increases.

Thermistor failure

i. *Silver Migration* This failure can occur due to one or more of: constant direct current bias, high humidity, and electrolytes (disc/chip contamination). Moisture finds its way into the thermistor and reacts. Silver (on the thermistor electrodes) turns to solution, and the direct current bias stimulates silver crystal growth across the thermistor element. The thermistor resistance decreases, eventually producing a short circuit.

ii. *Micro Cracks* Thermistors can crack due to improper potting materials if a temperature change causes contraction of the potting material, crushing the thermistor. The result is a thermistor that has erratic resistance readings and is electrically 'noisy'.

iii. *Fracture of Glass Envelope* Typically caused by mishandling of thermistor leads, this failure mechanism induces fractures in the glass coating at the lead/thermistor interface. These cracks may propagate around the thermistor bead resulting in increased resistance. Mismatching of epoxies or other bonding materials may also cause fracture.

iv. *Aging out of Resistance Tolerance* If thermistors are exposed to high temperatures over time, termed 'aging', their resistivity can change. Generally the resistivity increases, which results in a deceased temperature. Temperature cycling may be thought of as a form of aging. It is the cumulative exposure to high temperature that has the greatest influence on a thermistor component, not the actual temperature cycling. Temperature cycling can induce shifts if the component has been built into an assembly with epoxies or adhesives, which do not match the temperature expansion characteristics of the thermistor.

25.7.6 Other specialised resistors

Table 25.4: Other resistor types and uses

variable	type	material	application
temperature	thermistors	NTC - semiconductor oxide PTC - barium titanate	temperature control amplifier gain control voltage regulation – NTC current regulation – PTC flow control
strain	strain gauges	metal wire or foil	low pressure sensing
voltage	varistors (see chapter 10)	metal oxide silicon carbide	transient voltage protection
pressure	transducers microphones	carbon, ceramic	control application
humidity	-	carbon, metal film, thick film metal oxide	humidity sensors

25.8 Appendix: Carbon ceramic electrical and mechanical data and formula

Electrical parameter	units	value	mechanical	units	value
resistivity	Ω cm	3 to 30000	density	g/cm^3	2.25
Temperature coefficient	%per °C	-0.05 to -15	Coefficient of linear expansion	/ °C	$+4\times10^{-6}$ to $+10\times10^{-6}$
Voltage coefficient	% /kV/cm	-0.5 to -7.5	Bending strength	kg.m for 15cm diameter	30 to 60
Dielectric constant		5	Youngs modulus	N.cm^{-2}	3×10^6
inductance		negligible	Crushing strength	N cm^{-2}	12000
Thermal conductivity	W/cm^2 °C/cm	0.04			
Specific heat capacity	J cm^3 / °C	2.0			

$$\alpha = +1600 \times e^{-\log\rho/1.4} - 1350 \qquad (10^{-6}/°C \text{ or } ppm/°C)$$

$$\phi = -0.62 \times \rho^{0.22} \qquad (\%/kV/cm)$$

$$P_d = 2.6 \times (\Delta T)^{1.4} \times A_{surface} \qquad (W)$$

25.9 Appendix: Characteristics of resistance wire

Alloy type[a]	Resistivity, Ω cmil ft^{-1} 20 °C	Resistivity,[b] Ω cm^2 cm^{-1} × 10^6 20 °C	Resistance temp coefficient,[c] ppm °C^{-1}	Linear expansion thermal coefficient, cm/cm/°C × 10^6, 20–100 °C	Min tensile strength lb in^{-2} 25 °C[d]	Melting temp (approx), °C	Relative magnetic attraction	Density, g cm^{-3}, 20 °C	Heat capacity[e] J g^{-1} °C^{-1}	Thermo-electric potential to copper[f] (approx), V °C^{-1} × 10^6
80–20 Ni-Cr	650–675	108–112	+60 to +90 ± 20	12–18	100,000	1400	None	8.41	0.435	+6.0
Constantan	294–300	49–50	0 ± 20	14.5	60,000	1350	None	8.90	0.393	-45
Manganin	230–290	38–48	0 ± 15[c]	18.7	40,000	1020	None	8.192–8.41	0.406	–3.0, +1
Alloy 180	180	29.9	+180 ± 30	15.7–17.5	50,000	1100	None	8.90	0.385	-37
Alloy 90	90	14.9	+450 ± 50	16–17.5	35,000	1100	None	8.90	0.385	-26
Alloy 60	60	9.97	+500 to +800 ± 200	16.2–16.3	50,000	1100	None	8.90	0.385	-22
Alloy 30	30	4.99	+1400 to +1500 ± 300	16.4–16.5	30,000	1100	None	8.91	0.385	-14
Linear TC[a]	120	19.9	+4500 ± 400	12–15	70,000	1100	Strong	8.46	0.523	-40
Nickel A	60	9.97	+4800	13	60,000	1450	Strong	8.90	0.544	-22
High purity Ni[a]	50	8.31	+6000	13.3–15	50,000	1400	Strong	8.90	0.544	-22
Iron	61.1	10.15	+5000 to +6200	11.7 (20 °C)	50,000	1535	Strong	7.86	0.445	+12.2
Copper	10.37	1.72	+3900 to +4300	16.5 (20 °C)	35,000	1083	None	8.90	0.385	0
Evanohm[g]	800	133	0 ± 5	12.6	100,000	1350	None	8.10	0.448	+3.0
Karma[h]	800	133	0 ± 20	13.3	180,000	1400	None	8.10	0.435	+3.0
Alloy 800[i]	800	133	0 ± 5	15	150,000	1260	None	7.95		+2.5
Chromel R[j]	800	133	0 ± 10	13.5	95,000	1398	None	8.1	0.448	~+1.0
Moleculoy[k]	800	133	0 ± 5	13.3	130,000	1395	None	8.12	0.435	+3.0
Nikrothal LX[l]	800	133	0 ± 5	12.6	150,000	1410	None	8.1	0.460	+2.0
Kanthal DR[l]	812	135	0 ± 20	11.9	100,000	1505	Strong	7.2	0.494	-3.5
Mesoloy[k]	825	137.2	0 ± 10	13.5	100,000	1500	Strong	7.15	0.481	-3.3
Alloy 815[i]	815	135.5	+82	15.9	~115,000	1520	Strong	7.25	0.460	~-3.7
Alloy K-20[i]	815	135.5	0 ± 20	13	100,000	1530	Strong	7.25	~0.460	-3.5
Evanohm S[g]	825	137	0 ± 5	13	100,000	1350	None	7.13	0.460	+0.2

Metal	nΩm Resistivity
Aluminum	22.7
Copper	17.0
Gold	23.0
Iron	105.0
Nickel	78.0
Platinum	106
Silver	16.0
Tin	115
Tungsten	55.0
Zinc	62.0
Carbon-steel	180
Brass	60
Constantan	450
Invar	100
Manganin	430
Nichroma	1105
Nickel-silver	272
Monel metal	473
Kovar	483
Phosphor-bronze	93
18/8 stainless steel	897

25.10 Appendix: Preferred resistance values of resistors (and capacitors)

Specific resistance values have been standardised based on logarithmic values $\sqrt[E]{10}$ or $10^{\frac{1}{E}}$ where E is the number of resistors (logarithmic steps) within each decade. If the first resistance is one per unit, then the geometric progression for the E resistors is given by $1\times\sqrt[E]{10}^{\,n-1}$, for n = 1 to E. Common E values (IEC 60063) are *3*, 6, 12, 24, 48, 96, and 192. The E3 range is rare for resistors but not uncommon with capacitors, especially electrolytic capacitors which tend to have wider tolerances due to manufacturing processing limitations and constraints.

The E3 range has decade values based on 10, 22 (21.54), and 47 (46.4), which give a 50% error band.
The E6 range of 10, 15, 22, 33, 47, and 68 preferred values have a maximum error of 20%.
The E12 range of 10, 12, 15, 18, 22, 27, 33, 39, 470, 56, 68, 75, and 82 has a 10% error band.
The E24, E48, E96, and E192 ranges have resistance tolerance error bands of 5%, 2%, 1% and better than 1%, respectively. Resistors with a tolerance of better than ±½% are termed precision resistors.

Resistors are physically coded with 4, 5, or 6 colours bands, with numerical values (plus tolerance and temperature coefficient) assigned to the colours as shown below and in figure 25.1. Capacitors are not colour coded.

0 black		
1 brown	±1%	100ppm
2 red	±2%	50ppm
3 orange		15ppm
4 yellow		25ppm
5 green	±½%	
6 blue	±¼%	
7 violet	$\pm\frac{1}{10}$%	
8 grey	$\pm\frac{1}{20}$%	
9 white		
$\times\frac{1}{10}$ gold	±5%	
$\times\frac{1}{100}$ silver	±10%	

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Reading list

Philips, Book 3, Part 1c, Fixed Resistors, 1985.

Philips, Book 3, Part 1f, Varistors, Thermistors and Sensors, 1986.

Siemens, Components, 1986.

Siemens, NCT Thermistors, Data Book, 1986/87.

Rohm.com

Vishay.com

Hvrint.com

Problems

25.1. The resistance of a temperature dependent negative temperature coefficient resistor is given by

$$R(T) = Ae^{\frac{B}{T}}$$

where B = 3300 K and R = 10 Ω at 25°C. The resistive element has a thermal resistance to ambient of 45.5 K/W. Assume the maximum resistor temperature is 1000°C and absolute zero is -273°C.

(1) Calculate the temperature coefficient at 25°C.
[-0.037 or -3.7 per cent/K]

(2) When the non-linear resistor is dissipating power, what is the maximum attainable terminal voltage? At what temperature and current does this voltage occur at? Assume the ambient temperature is 25°C.
[58.3°C, 3.29 Ω, 0.73 W, 1.55 V, 0.47A]

(3) The non-linear resistance dependence on temperature can be 'linearised' by the parallel connection of a resistor. The resultant characteristic has an inflexion point, which is set at the mid-point of the required temperature operating range. Calculate the required parallel connected resistor if the mid-temperature point of operation is 58.3°C.
[2.2 Ω, 1 W]

(4) What series resistor must be added such that the maximum voltage condition occurs at 5 V across the series plus parallel combination?
[3.45 Ω, 6 W]

25.2. Derive a series of general formulae for the parts of problem 25.1.

$$\left[\alpha = -B / T^2; \quad \hat{T} = \tfrac{1}{2}B\left(1 - \sqrt{1 - 4T_a / B}\right); \quad R_p = R_{T_m}\left(\frac{B - 2T_m}{B + 2T_m}\right)\right]$$

25.3. Resistors coming off the production line are selected according to value and allocated to one of 12 bins for each decade.
Find the nominal centre value for each bin to give a range with equal ratios, and compare with the 'E12' series (1, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2, *10*).
Find the maximum percentage difference between the nominal value and the E12 value.
Show that the 12-step series corresponds to a ±10 per cent tolerance for practical resistors.
[4.5 per cent between 3.16 and 3.3]

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