RESISTOR FACTS AND FACTORS

A resistor is a device connected into an electrical circuit to introduce a specified resistance. The resistance is measured in ohms. As stated by Ohm's Law, the current through the resistor will be directly proportional to the voltage across it and inversely proportional to the resistance.

The passage of current through the resistance produces heat. The heat produces a rise in temperature of the resistor above the ambient temperature. The physical ability of the resistor to withstand, without deterioration, the temperature attained, limits the operating temperature which can be permitted. Resistors are rated to dissipate a given wattage without exceeding a specified standard "hot spot" temperature and the physical size is made large enough to accomplish this.

Deviations from the standard conditions ("Free Air Watt Rating") affect the temperature rise and therefore affect the wattage at which the resistor may be used in a specific application.

SELECTION REQUIRES 3 STEPS

Simple short-cut graphs and charts in this catalog permit rapid determination of electrical parameters. Calculation of each parameter is also explained. To select a resistor for a specific application, the following steps are recommended:

1. (a) Determine the Resistance.
(b) Determine the Watts to be dissipated by the Resistor.

2. Determine the proper "Watt Size" (physical size) as controlled by watts, volts, permissible temperatures, mounting conditions and circuit conditions.

3. Choose the most suitable kind of unit, including type, terminals and mounting.

STEP 1 DETERMINE RESISTANCE AND WATTS

Ohm's Law

(a) $R = \frac{V}{I}$ or $I = \frac{V}{R}$ or $V = IR$

Ohm's Law, shown in formula form above, enables determination of the resistance when the required voltage and current are known. When the current and voltage are unknown, or the best values not decided on, at least two of the three terms in Ohm's Law must be measured in a trial circuit.

(b) $P = I^2R$ or $P = VI$ or $P = \frac{V^2}{R}$

Power in watts, can be determined from the formulas above, which stem from Ohm's Law. R is measured in ohms, V in volts, I in amperes and P in watts.

Why Watts Must Be Accurately Known

Stated non-technically, any change in current or voltage produces a much larger change in the wattage (heat to be dissipated by the resistor). Therefore, the effect of apparently small increases in current or voltage must be investigated because the increase in wattage may be large enough to be significant. Mathematically, the wattage varies as the square of the current, or voltage, as stated in the formulas (b). For example, an increase of 20% in current or voltage will increase the wattage 44%. Figure 1 below graphically illustrates the square law relation. Hence, the actual current must be used in figuring the wattage and the increase in wattage due to apparently small changes, then determined in order to select the proper size resistor. Allowance should be made for maximum possible line voltage.

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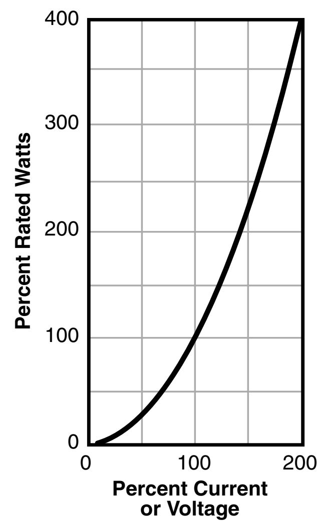

Fig. 1: Rapid increase of wattage with current or voltage.

STEP 2 POWER RATING OR PHYSICAL SIZE OF RESISTOR

A resistor operated at a constant wattage will attain a steady temperature which is determined largely by the ratio between the size (surface area) and the wattage dissipated, The temperature stabilizes when the sum of the heat loss rates (by radiation, convection and conduction) equals the heat input rate (proportional to wattage). The greater the resistor area per watt to be dissipated, the greater the heat loss rate and therefore the lower the temperature rise. The relation between the losses varies for different resistors.

Free Air Watt Rating

The wattage rating of resistors, as established under specified standard conditions, is defined as the "Free Air Rating" ("Full Rating" or "Maximum Power Rating"). Several standard methods of rating are in use based on different service conditions. The method of both the "National Electrical Manufacturers Association" (NEMA) and the "Underwriters' Laboratories, Inc." (UL) can be described as follows:

The relation of the "Free Air Watt Rating" of tubular type, vitreous enameled resistors to the physical size, is to be set at such a figure that when operated at their rated watts, the temperature rise of the hottest spot shall not exceed 300°C (540°F) as measured by a thermocouple when the temperature of the surrounding air does not exceed 40°C (104°F). The temperature is to be measured at the hottest point of a two-terminal resistor suspended in free still air space with at least one foot of clearance to the nearest object, and with unrestricted circulation of air.

A slightly different definition of temperature limit used as a basis for wattage rating, and which results in a slightly higher attained temperature, was originally established in military specification MIL-R-26 for wirewound resistors.

Characteristic V resistors are required to dissipate rated wattage in an ambient of 25°C without exceeding a maximum operating temperature of 350°C at the hottest spot. This corresponds to a temperature rise of 325°C in a 25°C ambient. Although MIL-R-26 permits a 25°C greater temperature rise than NEMA or UL, the reference ambient for the latter two is 15°C higher. Consequently, the difference in attained temperature between the two systems is only 10°C. The curves in Fig. 2 show the relation between temperature rise and wattage for various specifications. Note the differences in the permissible rise for each specification.

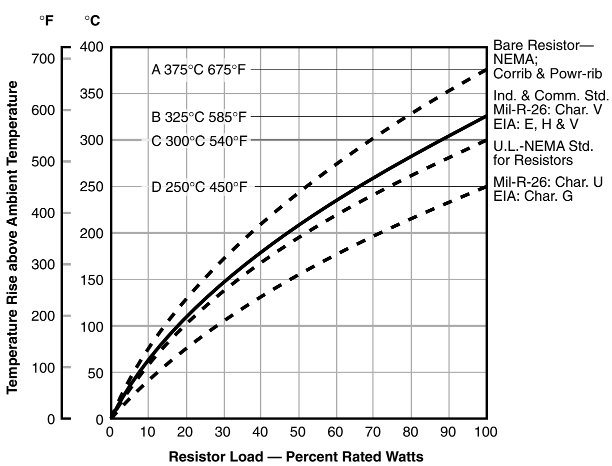

Fig. 2: Approximate hot spot temperature rise of a resistor in free air for various specifications.

The absolute temperature rise for a specific resistor is roughly related to the area of its radiating surface. It is also dependent upon a number of other factors, however, such as thermal conductivity of the core and coating materials, emissivity factor of the outer surfaces, ratio of length to diameter, heat-sink effect of mountings, and other minor factors.

The maximum permissible operating temperature for a given resistor is basically determined by the temperature limitations imposed by the materials used in its construction. Generally speaking, these limits cannot be sharply defined in terms of temperature alone. Other factors such as resistance stability versus time, deterioration rates of insulation and moisture-resistance characteristics, type and size of resistance wire, all enter into consideration of "acceptable service life."

For these reasons, the precise temperature limits corresponding to 100% rated wattage are somewhat arbitrary and serve primarily as design targets. In the last analysis, once a wattage rating has been assigned on the basis of an empirical hot spot limit, the verification of its correctness must be established through long term load-life tests based on performance and stability standards rather than the measurement of hot spot temperature. Maximum limits are stipulated for parameter changes as a result of various tests, including a 2000 hour load-life test.

It is also assumed that the temperature rise at a given wattage is independent of the ambient temperature in which this wattage is being dissipated. Therefore, for high ambient temperatures, the operating wattage should be limited in accordance with the curves of Fig. 3. Although the assumption that temperature rise is independent of ambient is not exactly true, the approximation is sufficiently close for all practical purposes and, therefore, has been adopted for derating purposes.

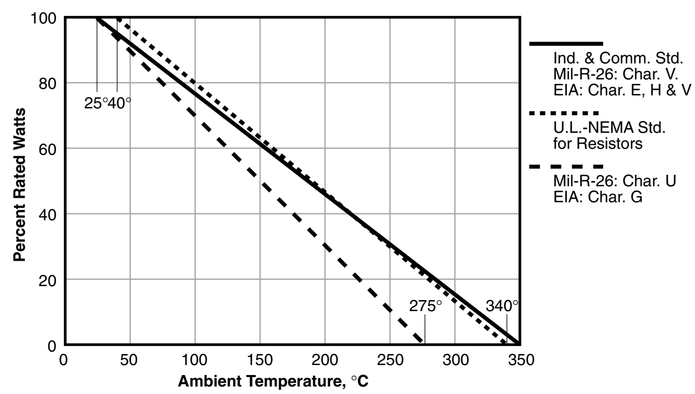

Fig. 3: Derating for ambient temperature.

Despite the above variables, figures may be cited in terms of "watts dissipated per square inch of winding surface" for a given temperature rise. For power type resistors operating at 300°C rise above ambient, this figure varies between approximately 6.3 watts per square inch for large resistors (175 watt) to about 9 watts per square inch for smaller resistors (12 watt). It should also be observed from Fig. 2 that temperature rise is not directly proportional to wattage dissipated. Note, for example, that at 50% rated wattage, the temperature rise still remains about 70% of that at full rating.

The wattage ratings used in this catalog, unless otherwise stated for certain types, are on the basis of a nominal operating temperature of 350°C at full rating. There are two general categories of power resistors for which the 350°C nominal temperature limit does not apply. One is that class of power-precision resistors where high stability is a salient feature, in which case the operating temperature is nominally limited to 275°C. The other category includes all exposed ribbon wire resistors (see description of Corrib® and Powr-Rib®) which are rated for 375°C (675°F) maximum temperature rise when measured on the wire per NEMA standards.

Temperature Distribution on a Resistor

The temperature rise varies (following a curve) along the length of the resistor with the hot spot at the center-top (of a horizontal tube) and the ends at approximately 60% of the maximum temperature rise. The terminals themselves are still cooler. When the resistor is vertical, the hot spot shifts upwards a little and the top end is hotter than the bottom. The standard "Free Air Watt Rating," however, is used regardless of position.

Resistor Selection

STEPS 3 SELECT A RESISTOR

Choose the most suitable resistor meeting the requirements of the application. Standard resistors carried in stock should be considered first. If a suitable resistor cannot be found in the standard sizes or resistance values, then select a non-standard resistor from the range on available sizes (consult factory).

APPLICATION WATT RATING

To allow for the differences between the actual service conditions and the “Free Air Watt Rating” it is a general engineering practice to operate resistors at more or less than the nominal rating. The details by which such ratings can be estimated are given in the following pages. Most thermal calculations, however, involve so many factors which are usually not accurately known, that at best they are only approximations.

The most accurate method of determining or checking the rating is to measure the temperature rise in a trial installation. A thermocouple (made of #30 B & S gage wire) is recommended for the measuring element. Even measurements made with a thermocouple will vary slightly with different samples and techniques. The factors which affect the temperature rise act independently of each other and are summarized as follows:

1. Ambient Temperature
As the maximum permissible operating temperature is a set amount, any increase in the ambient temperature subtracts from the permissible temperature rise and therefore reduces the permissible watt load.

2. Enclosure
Enclosure limits the removal of heat by convection currents in the air and by radiation. The walls of the enclosure also introduce a thermal barrier between the air contacting the resistor and the outside cooling air. Hence, size, shape, orientation, amount of ventilating openings, wall thickness, material and finish all affect the temperature rise of the enclosed resistor.

3. Grouping
When resistors are close to each other they will show an increased hot spot temperature rise for a given wattage because of the heat received by radiation from each other and the increased heat per unit volume of air available for convection cooling.

4. Altitude
The amount of heat which air will absorb varies with the density, and therefore with the altitude above sea level. At altitudes above 100,000 feet, the air is so rare that the resistor loses heat practically only by radiation.

5. Pulse Operation
This is not an environmental condition but a circuit condition. As a pulse of power, when averaged over the total on and off time, results in less heat per unit time than for continuous duty, the temperature rise is affected. This may permit higher power during the pulses. The conditions must be expertly considered for conservative rating. The open-wound “Powr-Rib®” resistor construction is most suitable.

6. Cooling Air
Forced circulation of air over a resistor removes more heat per unit time than natural convection does and therefore permits an increased watt dissipation. Liquid cooling and special conduction mountings also can increase the rating.

7. Limited Temperature Rise
It is sometimes desirable to operate a resistor at a fraction of the Free Air Watt Rating in order to keep the temperature rise low. This may be to protect adjacent heat sensitive apparatus, to hold the resistance value very precisely both with changing load and over long periods of time and to insure maximum life.

8. Other Considerations
High Resistance. High resistance units, which require the use of very small diameter wire, generally should operate at reduced temperature for maximum reliability.

High Voltage
A maximum voltage gradient of 500 volts R.M.S. (705 volts peak) per inch of winding length is recommended under normal conditions. For higher gradients in pulse applications or for other special conditions such as oil immersion, consult factory.

High Frequency
Non-inductively wound resistors are generally required for use at high frequencies.

Military and Other Specifications
The special physical operating and test requirements of the applicable industrial or military specification must be considered. Military specification resistors should be ordered by their MIL numbers.

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ENVIRONMENTAL FACTORS—EFFECT ON THE POWER RATING OF COMPONENTS

All the components of an electrical apparatus — resistors, rheostats, capacitors, transformers, chokes, wiring, terminal boards, rectifiers, transistors, electronic tubes, etc.—have their own limitations as to the maximum temperature at which they can reliably operate. The attained temperature in service is the sum of the ambient temperature plus the temperature rise due to the heat dissipated in the apparatus.

The temperature rise of a component is affected by a number of factors. The graphs and discussions which follow, amplify and supplement the factors on the previous page.

Note that the Multiplying Factors given on the Short Cut Chart, on page 96 are the reciprocals of the "Percent Load Ratings" shown on the graphs in this section. The percent figures are, of course, expressed as decimals before finding the reciprocals.

Ambient Temperature Derating

Fig. 4 shows the percent of full load which power resistors can dissipate for various high ambient temperatures.

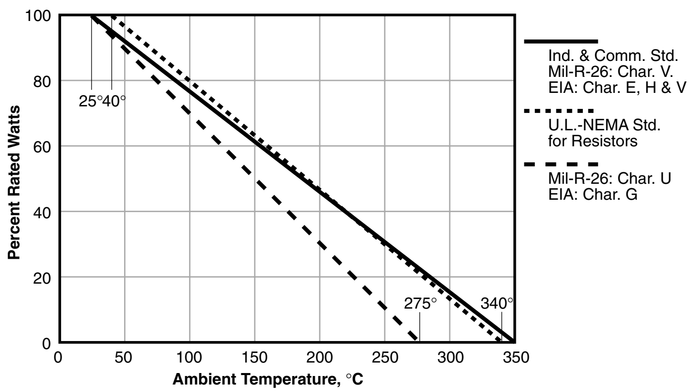

Fig. 4: Derating of Resistors for High Ambient Temperatures.

Derating Due to Enclosure

The amount of derating required, if any, because of enclosure is affected by a number of factors, most of which are hard to determine accurately. The watts per square inch of surface, size, shape, orientation, wall thickness, material, finish and amount and location of ventilating openings all play a part. Fig. 5 serves to indicate for a particular set of conditions how the temperatures varied with the size of enclosure for a moderate size power resistor.

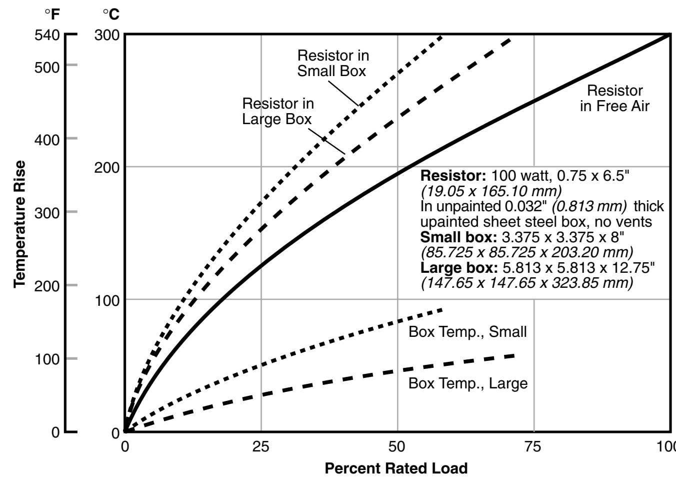

Fig.5: Example of Effect of Size of Enclosure on Temperature Rise of An Enclosed Resistor.

Derating Due to Grouping

The temperature rise of a component is affected by the nearby presence of other heat-producing units, such as resistors, electronic tubes, etc. The curves in Fig. 6 show the power rating for groups of resistors with various spacings between the closest points of the resistors, assuming operation at maximum permissible hot spot temperature. If resistors are to be operated at lower hot spot temperatures, the amount of derating for grouping can be reduced.

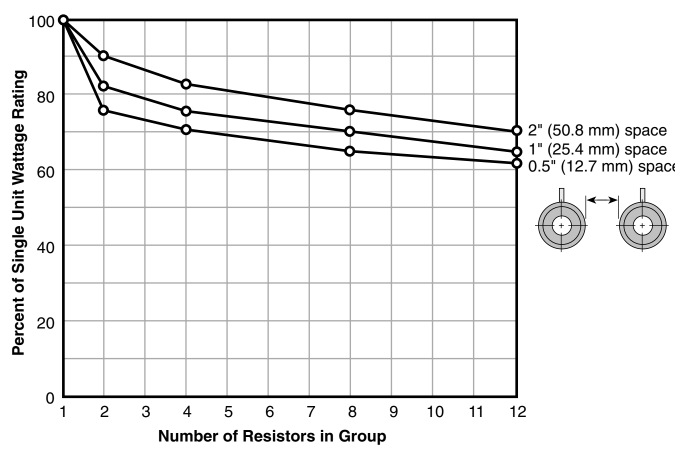

Fig.6: Derating of Resistors to Allow for Grouping

Derating for Altitude

The curve in Fig. 7 shows the proportional watts for various altitudes, assuming standard atmospheric conditions.

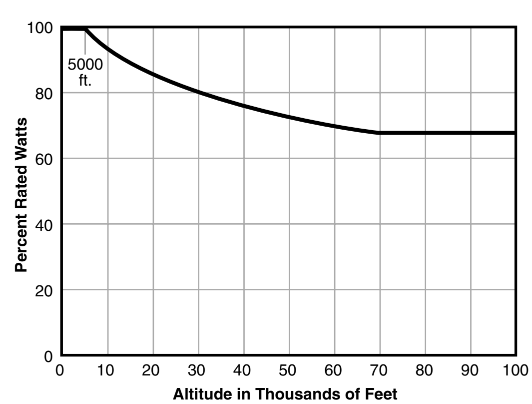

Fig. 7: Derating for Altitude

Resistor Selection

Pulse Operation

Unlike the environmental factors, which result in reduction of the watt rating, pulse operation may permit higher power in the pulses than the continuous duty rating.

The NEMA has set up certain standard duty cycles for motor control resistors and the resistor ratings for some of these conditions are shown in Fig. 8.

The curves in Figures 10,11,12 and 13 illustrate the more general case of various combinations of on and off time for specified loads up to 1000% for a continuous series of pulses. Intermediate loads can be approximated by interpolation. The "on-time" at which each curve flattens out also indicates the maximum on-time for single pulses (with enough off-time for cooling to ambient). Additional data on single pulses is given by Fig. 9. Resistors will reach about 75% of the rated maximum temperature rise in approximately 5 to 8 pulses and level off at maximum rise in another 10 to 20 cycles, depending on percent load, size, type, etc. Any curve passing above the intersection of the designated on and off-times indicates a percent load which can be used. A resistor operated at the rating of an interpolated curve through the point of intersection would operate at maximum rated temperature rise.

The exact temperature rise, of course, varies with each resistor, depending on size, ohms winding, etc. The curves shown indicate the approximate rise for typical units only, as a band or range of values actually exists for each percent load.

Ratings at over 1000% are not recommended except for Powr-Rib® resistors. Curves for intermediate size resistors can be roughly estimated by comparison with the sizes given.

Ratings for single pulses in the milli-second range (and up to 1 to 2 seconds) require individual calculation. This is because the ratings vary greatly with the resistance, or more specifically with the actual weight and specific heat of the resistance alloy used. Calculation is based on the assumption that all of the heat generated in the pulse goes to raise the temperature of the resistance wire.

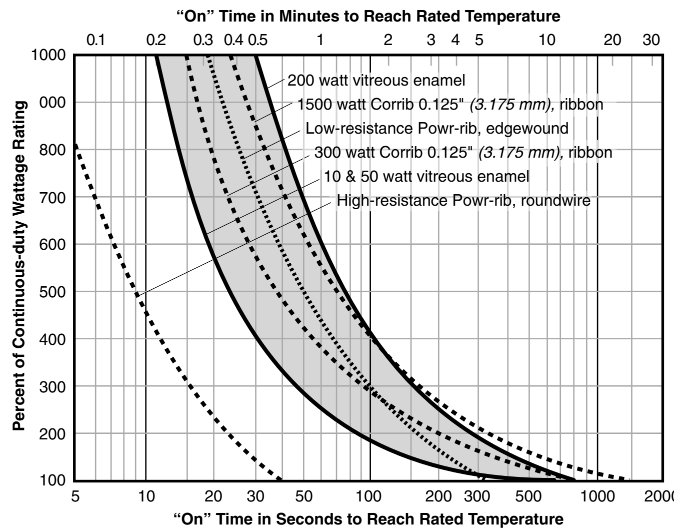

Fig. 9: Time Required for Typical Resistors to Reach Rated Operating Temperatures at Various Watt Loads.

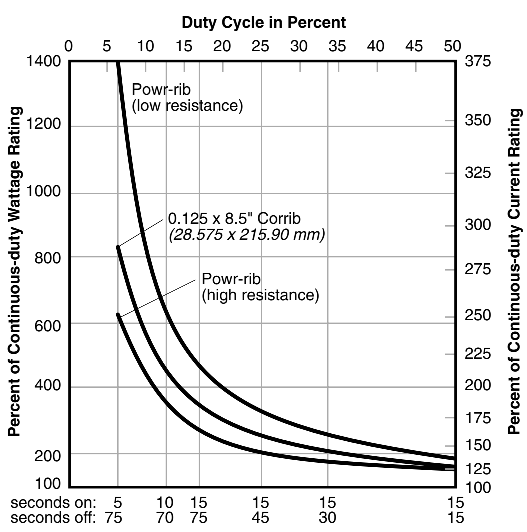

Fig. 8: Percent of Continuous Duty Rating for Resistors for Typical NEMA Duty Cycles.

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PULSE OPERATION — COOLING — LIMITED TEMPERATURES

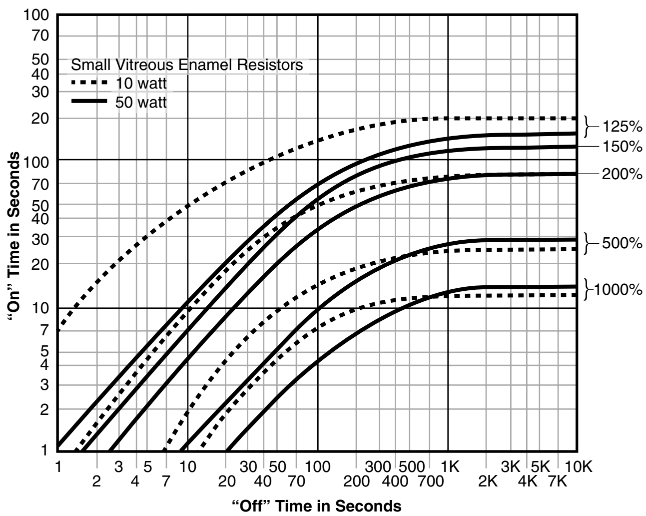


Fig. 10: 10 Percent of Continuous Duty Rating for Pulse Operation of small to Medium Size Vitreous Enameled Resistors.

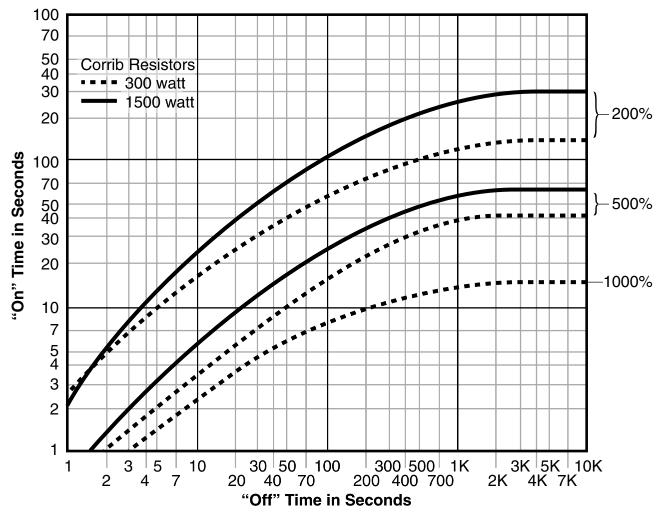


Fig.12: Percent of Continuous Duty Rating for Pulse Operation of CORRIB®, Corrugated Ribbon Resistors.

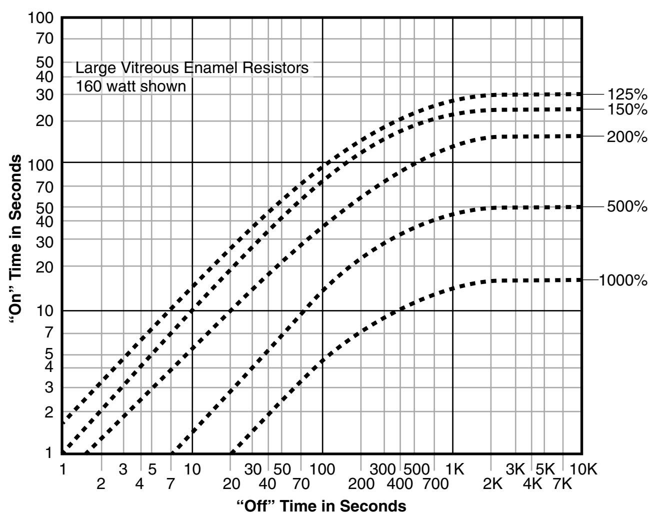


Fig. 11: Percent of Continuous Duty Rating for Pulse Operation of Large Vitreous Enameled Resistors.

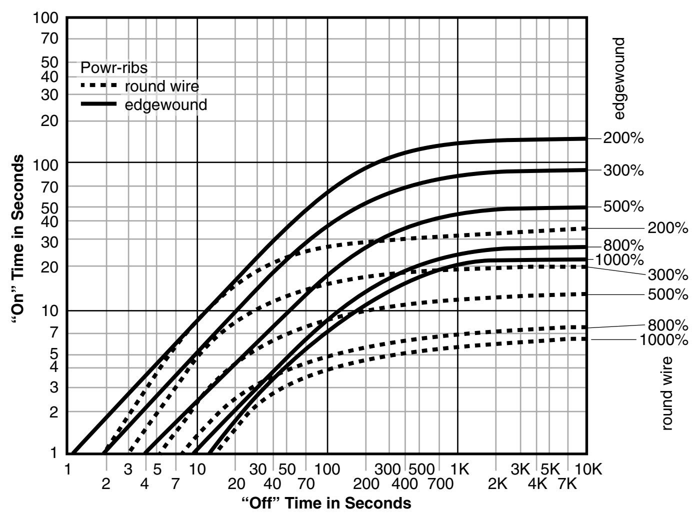


Fig. 13: Percent of Continuous Duty Rating for Pulse Operation of Powr-Rib®, Bare Resistors

Cooling Air

Resistors can be operated at higher than rated wattage when cooled by forced circulation of air. A typical curve is illustrated in Fig 14. The curve tends to level off at higher velocities as excessive hot spots develop where the air flow does not reach all parts uniformly.

Limited Temperature Rise

When it is desired to operate a resistor at less than maximum temperature rise, the percent watts for a given rise can be read from "Temperature Rise vs. Resistor Load" Fig 2 graph on page 91.

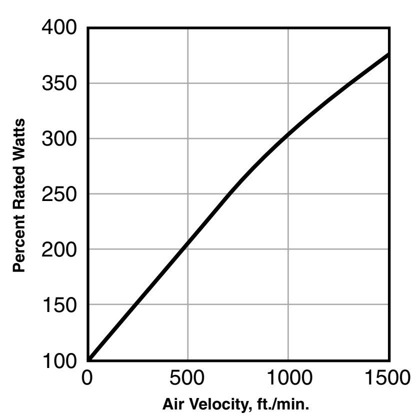


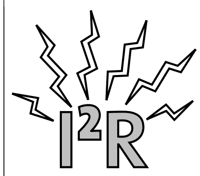
Fig. 14: Percent of Free Air Rating for Typical Resistor Cooled by Forced Air Circulation.

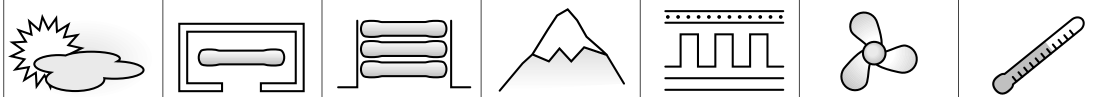
Resistor Selection

SHORT-CUT CHART METHOD TO FIND REQUIRED SIZE (as affected by application conditions)

1. For each Condition, locate the relevant value on the scales below and record the corresponding Factor (F_1 to F_7). Note: The Standard Free Air Condition Factor is always 1.
2. Multiply the Factors together.
3. Multiply the Watts by the product obtained from 2 above.

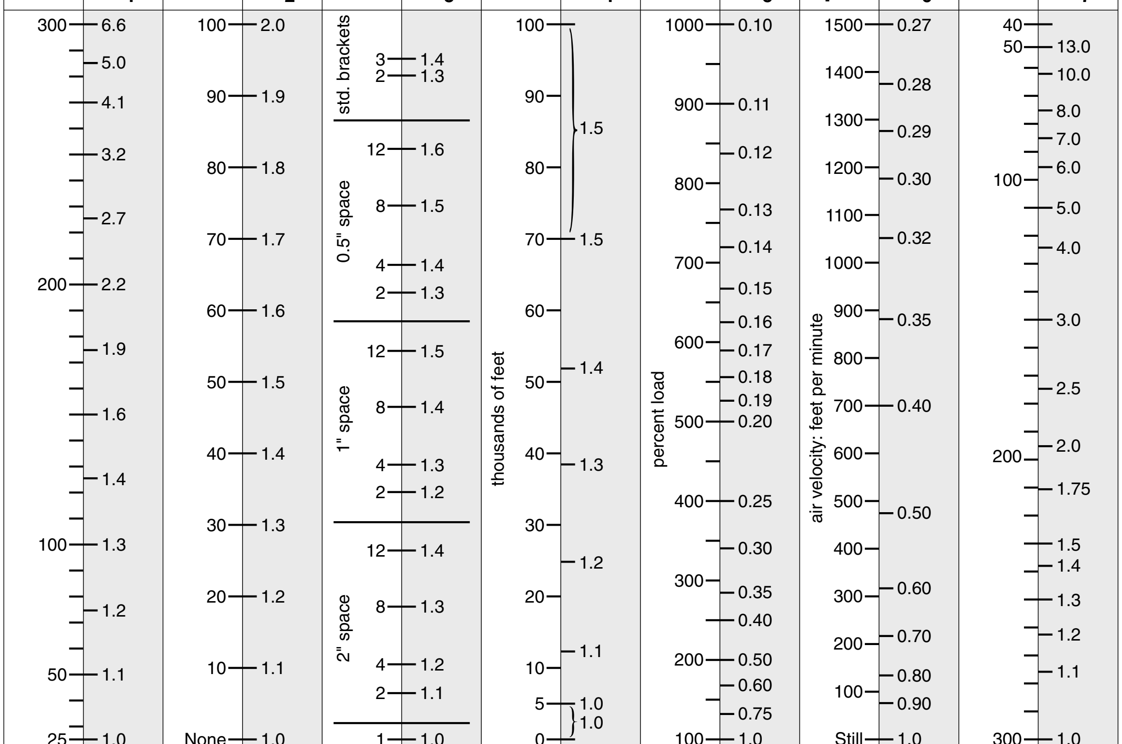
Watts | **Application Conditions**: Ambient Temperature | Enclosure | Grouping | Altitude | Pulse Operation | Cooling Air | Limited Temp. Rise





Record the watts to be dissipated as set by your circuit conditions.

Standard free air conditions



watts to be dissipated	× factor	× factor	× factor	× factor	× factor	× factor	× factor
	Temperature at installation includes room temperature plus temperature rise due to adjacent heat sources.	Factors apply approximately for average sheet metal boxes of dimensions such that watts per sq. in. of surface are in the range of 0.2 to 0.4.	Factors apply to uniformly spaced banks of parallel resistors with spacing as shown.	Factors apply to altitudes show. No derating is required for altitudes to 5000 ft. above sea level.	Percent load for pulse operation must first be determined from graphs and data on page xx.	Factors are approximations only. Effectiveness of cooling varies with installation.	Low temperatures may be desired because of adjacent apparatus, increased stability or maximum reliability.

EXAMPLE

Four resistors, each dissipating 115 watts, are to be mounted in a group. Spacing is to be 2" surface to surface. Ambient to be 50°C (122°F). Enclosure to be total. Other factors standard. Determine Watt Size required.

Operation (1) On Ambient Temperature scale locate 50°C. Note and record F_1 = 1.1 as shown. Locate and record the other factors.

F_1		F_2		F_3		F_4		F_5		F_6		F_7
50°		100%		4@2"				Standard Conditions				
1.1	x	2.0	x	1.2	x	1	x	1	x	1		1

Operation (2) Multiply the factors together = 2.64
Operation (3) 115 Watts x 2.64 = 304 Watts Free Air Watt Size Rating required for each resistor.

TEMPERATURE COEFFICIENT OF RESISTANCE

The resistance alloys used for all except the lowest ohmic values show such little change with temperature that in most power circuits the resistance is considered constant. Actually there may be changes at full load of -4% to +8% of the initial resistance. The change is attributed in most part to the "temperature coefficient of resistance" (TCR) which is the change in resistance expressed as "parts per million per degree centigrade of temperature" (ppm/°C).

For special applications which require very constant resistance, it may be necessary to specify the maximum permissible TCR for the range of temperature involved. This would limit the choice of wire to only certain types of resistance alloys. The commonly known low TCR alloys in the 800 ohms per circular-mil-foot class consist largely of nickel and chromium alloyed with small amounts of aluminum and either copper or iron. Other low resistivity alloys, 294 ohms per circular-mil-foot, consist primarily of nickel and copper with only traces of other metals.

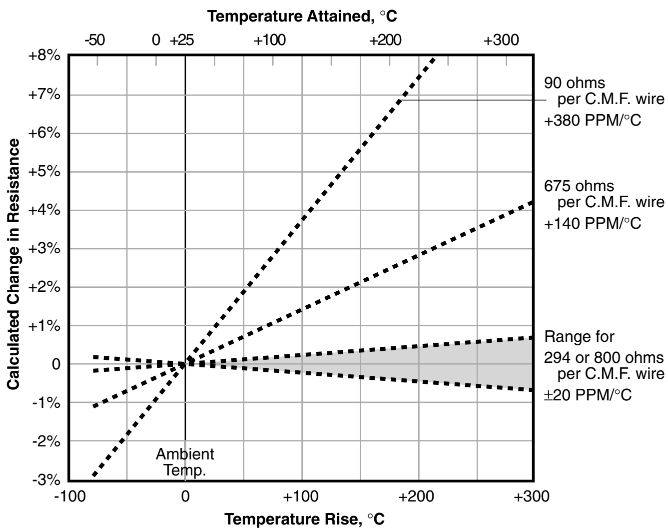


Fig. 15: Calculated change in resistance with nominal TC assumed constant.

Both of these wire classes are rated by the wire manufacturers as having a TCR of 0±20ppm/°C. The expression "0±20ppm/°C" implies that, although the nominal value of the TCR is zero, the actual value may lie anywhere within the tolerance range of –20ppm/°C to +20ppm/°C.

For other resistance wires such as the widely used nickel-chromium-iron, for example, a nominal value of +140ppm/°C is given. Actually, however, a tolerance of ±30ppm is applicable so that the TCR may range between the limits of +110 to +170ppm/°C.

Unfortunately, the TCR of a completed power resistor is generally somewhat different from that of the original wire. This is because the TCR may be affected by such factors as heat treatment during processing, and materials and methods of construction. Without special controls and precautions, the TCR over the range of 25°C to 300°C rise may increase to as much as

0±80ppm from the original 0±20ppm for certain types of wire on vitreous enameled resistors. Theoretical changes in resistance with temperature are shown in Fig. 15.

The circuit designer should carefully consider the actual needs of the circuit before specifying limits on the TCR of a desired resistor. Wherever possible it is best to select a resistor for a critical application so that it operates at a low temperature rise. This will also provide the maximum stability over a long period. For low TCR (and other) applications, Ohmite can provide resistors with an "Ohmicone" (silicone-ceramic) coating. "Ohmicone" is processed at much lower temperatures than vitreous enamel and therefore makes control of TCR and tolerance easier. Data on the TCR and other properties of various alloys is given on page 98.

Resistor Selection

RESISTANCE ALLOYS AND USES

A number of different resistance alloys are used in winding resistors and rheostats as shown in Fig. 16. The general use for each alloy is indicated by the column headed, “Resistance Range for Which Used.” Whether a particular alloy can be used on a specific resistor can be estimated by dividing the given resistance by the area of the given winding space and determining whether the quotient falls within the limits given hereafter. The “high resistance” alloys cover the range from approximately 10 to 25,000 ohms per square inch of winding area, the “low to medium” type from 5 to 400 ohms and the “very low resistance” alloys from less than an ohm to 250 ohms. It should be noted that the “Ohms per Square Inch” ranges overlap considerably, indicating that in many instances a given resistor could use any of several alloys. Both the upper and lower limits of the ranges are only approximate and in general can be extended somewhat when necessary.

The actual temperature coefficient of a complete resistor is generally greater than the nominal for the wire alone. The approximate change in overall resistance at full load is shown in the table.

Other Alloys
In addition to the alloys tabulated which show small changes in resistance with temperature, there are others which sometimes have to be used for very low resistance units. These alloys have higher temperature coefficients, which limit their use to applications where the change in resistance with load is not important. An example is No. 60 alloy, which has a resistance of 60 ohms per circular-mil-foot and a temperature coefficient of +700ppm/°C.

Ballast Wire
There are other alloys which are selected especially for their high temperature coefficient of resistance. These are used for so-called “ballast” resistors where a large change in resistance is desired with a change in load. A typical ballast wire is Nickel, which has 58 ohms/cmf and a temperature coefficient of +4800ppm/°C. Others are “Hytemco” and “Balco” at 120 ohms/CMF and a TC of +4500pp /°C.

ASTM Alloy Class*	Alloy Composition (Approximate)	Ohms per CMF	Trade Names	Mean Temp Coeff. of Res. ppm/°C	Temperature Range for TCR °C	Resistance Range for Which Used	Average Resistance Change at Full Load**
1a	Nickel base, non-magnetic Ni 75%, Cr 20% plus Al, Cu, Fe, etc.	800	Evanohm Karma Moleculoy Nikrothal L	0 ± 20	-65 to + 250	Very high, Medium and up, for low temp. coeff.	Under ± 1% to ± 2%
1b		800		0 ± 10	-65 to + 150		
2a	Iron base, magnetic Fe 73%, Cr 22.5%, Al 4.5% (plus Co in one alloy)	800	Alloy 815-R Kanthall Dr Mesaloy	0 ± 20	-65 to + 200	Alternate sometimes for Class 1	Under ± 1% to ± 2%
2b		800		0 ± 10	0 to + 150		
3a	Nickel-Chromium 80% — 20%	650	Chromel A Nichrome V Nikrothal B Protoloy A Tophet C	+ 80 ± 20	-65 to + 250	High and medium	+ 4 to + 5%
3b		675		+ 60 ± 20			
4	Nickel-Chromium-Iron 60%—16%—24%	675	Chromel C Electroloy Nichrome Nikrothal 6 Tophet C	+ 140 ± 30	-65 to + 200	High and medium	+ 5 to + 8%
5a	Copper-Nickel 55% — 45%	300	Advance Copel Cupron Cuprothal 294 Neutroloy	0 ± 20	-65 to + 150	Low and low to medium for low temp. coeff.	Under ± 1% to ± 2%
5b				0 ± 40			
6	Manganin 13% Mn, 87% Cu	290	Manganin	0 ± 15	+ 15 to + 35	Low and low to medium for low TC near 25°C	Under ± 1% to ± 2%**
7	Copper-Nickel 77% — 23%	180	180 Alloy Cuprothal 180 Midohm	+ 180 ± 30	-65 to + 150	Very low	+ 5% to + 8%
9	Copper-Nickel 90% — 10%	90	90 Alloy 95 Alloy Cuprothal 90	+ 450 ± 50	-65 to + 150	Very low	+ 5% to + 10%

*American Society for Testing Materials. Tentative Specification B267-68.
**For resistor with 300°C hot spot rise from 25°C ambient except 54°C rise for Manganin.

Fig. 16: Table of Resistance Alloys Generally Used for Resistors and Rheostats.