

Thermal Analysis and Design in Electronic Circuits

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Introduction

This note briefly discusses the issues involved with heat generation and removal in electronic components. Instructions are given for selecting an appropriate heat sink when required.

Heat Removal in Resistors

A typical resistor has a maximum power rating given when the ambient temperature is 25 degrees C. The allowable power dissipated has to be reduced when the ambient temperature is higher. At the maximum operating temperature (typically between 100 and 150 degrees C) the allowable power dissipation becomes zero. For temperatures in between the power is linearly de-rated in proportion to temperature. This is illustrated in Figure 1.

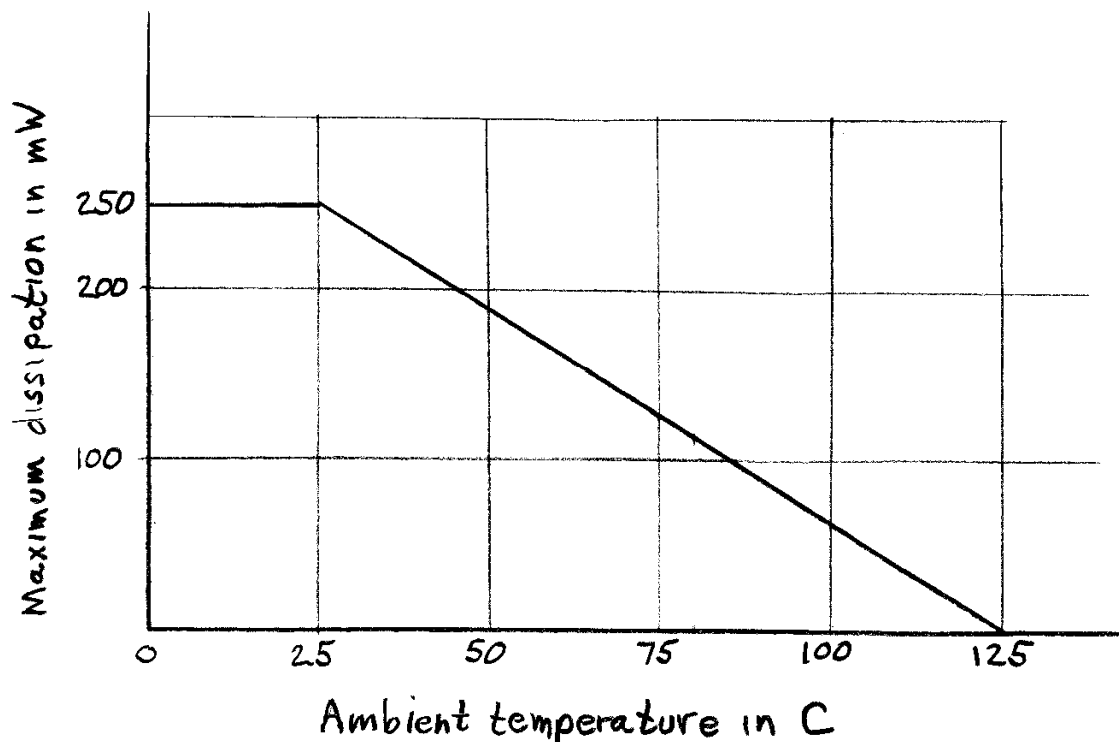


Figure 1: Power derating plot

It might be inferred from this discussion that the allowable power dissipation increases when the ambient temperature is less than 25 degrees C. This is not generally true and depends more on allowable internal current densities than absolute temperatures. Do not

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make assumptions – always check information from the manufacturer about operation the part in this mode.

As an example, consider a common $\frac{1}{4}$ watt carbon film resistor that can dissipate up to $\frac{1}{4}$ watt when the ambient temperature is 25 degrees C and has a maximum operating temperature of 125 degrees C. For each degree that the ambient temperature is above 25 the maximum power rating of the resistor decreases by 0.0025 Watts. Thus, if the maximum ambient temperature is 60 degrees C then the maximum allowable power dissipation of the resistor is decreased to 0.16 Watts. One thing to keep in mind is that when dissipating maximum allowable power the part is extremely hot and will quickly burn a finger that touches it. For example, a $\frac{1}{4}$ watt resistor dissipating its maximum power will have a surface temperature well over 100 C!

It is common practice to design for a power dissipation of no more than about one-half the rated power dissipation at the maximum operating temperature. This practice significantly reduces the maximum operating temperature and extends the useful life of the component considerably. In the previous example, the resistor would not be made to dissipate more than about 0.08 Watts.

The first thing to do in the design is to determine the actual maximum power the resistor will dissipate and to know the maximum design temperature (typically 60 degrees C but could be over 100 degrees C). Then the appropriate power rating for the resistor is selected so that the maximum power dissipated is about half the rated power dissipation at the maximum operating temperature. Note that high power resistors are intended to be mounted on a suitable heat sink. A 100 watt resistor will seriously overheat if not properly mounted. Always study the manufacture's recommended methods for heat removal.

Heat Removal in Solid-State Devices

Managing power dissipation in semiconductor components is the same as for resistors. The most important operating parameter is the junction temperature. If the junction temperature is too high the part will not work properly and may even be destroyed. The typical maximum junction temperature is 125 degrees C although in some special cases the temperature may be as high as 175. As with resistors, the useful operational life can be extended considerably if the maximum junction temperature is limited to much less than the rated value. A good value is from 25 to 50 degrees less than rated.

The case of many semiconductor components is designed so that a suitable heat sink can be mounted. The allowable amount of power that can be dissipated depends on the ability of the heat sink to conduct the heat away. Because the manufacturer can not know what heat sink you are going to use, the manufacturer rates the power dissipation in terms of an infinite heat sink that holds the case temperature at 25 C. This does not mean that the power dissipation could go to infinity as there is the internal thermal resistance to the

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case. Power dissipation must still be limited so that the junction temperature is no higher than the maximum rated.

Here is the “Ohm’s” law of temperature: The junction temperature is equal to the power dissipated multiplied by the thermal resistance to ambient plus the ambient temperature. This is in equation form as follows:

$$T_j = P_d * \theta_{ja} + T_a \quad \text{Eq. 1}$$

Temperature is in degrees C, power dissipation is in Watts, and thermal resistance is in Watts per degree C. Note that temperature is analogous to electrical voltage, power is analogous to electrical current, and thermal resistance is analogous to electrical resistance. The symbol, Q, is often used in thermal calculations to represent heat flow, i.e. power.

Equation 1 can also be expressed as:

$$\theta_{j_{\max}} = (T_{j_{\max}} - T_{a_{\max}}) / P_{d_{\max}} \quad \text{Eq. 2}$$

$$P_{d_{\max}} = (T_{j_{\max}} - T_{a_{\max}}) / \theta_{ja} \quad \text{Eq. 3}$$

$$T_{a_{\max}} = T_{j_{\max}} - (P_{d_{\max}} * \theta_{ja}) \quad \text{Eq. 4}$$

Equation 1 is used for analyzing an existing system. Equation 2 is used for designing the heat sink system. Equations 3 and 4 are useful to establish design limits.

The thermal resistance from the junction to ambient is generally composed of two or three components. In the situation of when no heat sink is used, the total thermal resistance is the sum of the junction to case thermal resistance and the case to ambient thermal resistance as shown below.

$$\theta_{ja} = \theta_{jc} + \theta_{ca} \quad \text{Eq. 5}$$

The value of a heat sink is that it reduces the thermal resistance from the case to ambient. When a heat sink is used the total thermal resistance is the sum of the internal junction to case thermal resistance plus the thermal resistance from the case to the heat sink plus the thermal resistance of the heat sink to ambient.

$$\theta_{ja} = \theta_{jc} + \theta_{cs} + \theta_{sa} \quad \text{Eq. 6}$$

The thermal resistance from the case to the sink is made small (typically less than 1 C/W) by using what is known as heatsink compound which is thermally conductive and fills the inherent air gaps. Without heatsink compound the thermal resistance between the case and the sink can be several times larger.

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Table 1 shows some typical values of power dissipation and thermal resistances for common transistor cases. Always check the manufacturer's data for a specific part as these numbers can vary a lot depending on internal construction. For example, integrated circuits tend to have much higher thermal resistances from the junction to the case than plain transistors.

| Case | Maximum possible power dissipation in Watts | | | θ in deg C / Watt | | | |
|--------|---|---------------|-------------|--------------------------|---------------|---------------|---------------|
| | Pd infinite HS | Pd good HS | Pd no HS | θ_{jc} | θ_{ca} | θ_{cs} | θ_{sa} |
| TO-3 | 100 | 60 | 5 | 0.5 | 18 | 0.5 | 0.5 |
| TO-220 | 25 | 15 | 2 | 3 | 45 | 1 | 2 |
| TO-5 | 4 | 2.5 | 1 | 20 | 75 | 5 | 15 |
| TO-18 | 2 | 1.2 | 0.5 | 40 | 160 | 10 | 30 |
| TO-92 | 1 | 0.6 | 0.33 | 60 | 240 | 40 | 60 |

Table 1: Typical semiconductor thermal data

A common mistake is to choose a part with a higher power rating than is needed and then assume that all is well. The power rating of *all* components is based on proper methods being applied to remove the heat. Fail to remove the heat and the component will malfunction or be destroyed. Pay close attention to the manufacture's application information for parts that must dissipate heat. In some cases the component leads form part of the heat sinking system and must not be too short.

Heat sinks

The purpose of a heat sink is to provide a low thermal resistance from the case of a component to the ambient air. Heat is both conducted to the air and radiated. A heat sink is constructed with a high thermal conductivity material such as aluminum and is made so as to have a large surface area for efficient heat transfer to the surrounding air. Heat sinks are often black anodized to increase thermal radiation. In the absence of forced air, convective air currents will conduct thermal energy away from the heat sink. Thus, it is very important for heat sinks to be physically mounted such that convective air currents can exist. A heat sink in a closed box is of little use. Thermal energy is never destroyed. It always accumulates (i.e. temperature rises) when it can not dissipate into the surroundings. Fans are often used to improve thermal transfer.

Heat sinks are typically rated in terms of temperature rise for a given power and given air flow. This data is generally provided as a plot. It is wrong (and advertises that the questioner is a newbie) to ask the question, "What size heat sink will get rid of 5 watts?" The answer could range from small to huge depending on what is actually needed. Figure 2 is a typical plot used to present heat sink data. Note that there are two curves and that each curve uses a different set of axis as shown. One curve shows the temperature rise for a given power dissipation in free convection. This is the curve you most commonly use. When forced air flow is needed, the other curve shows the effective thermal

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resistance for a given air flow. Use whichever curve is applicable to your situation and ignore the other.

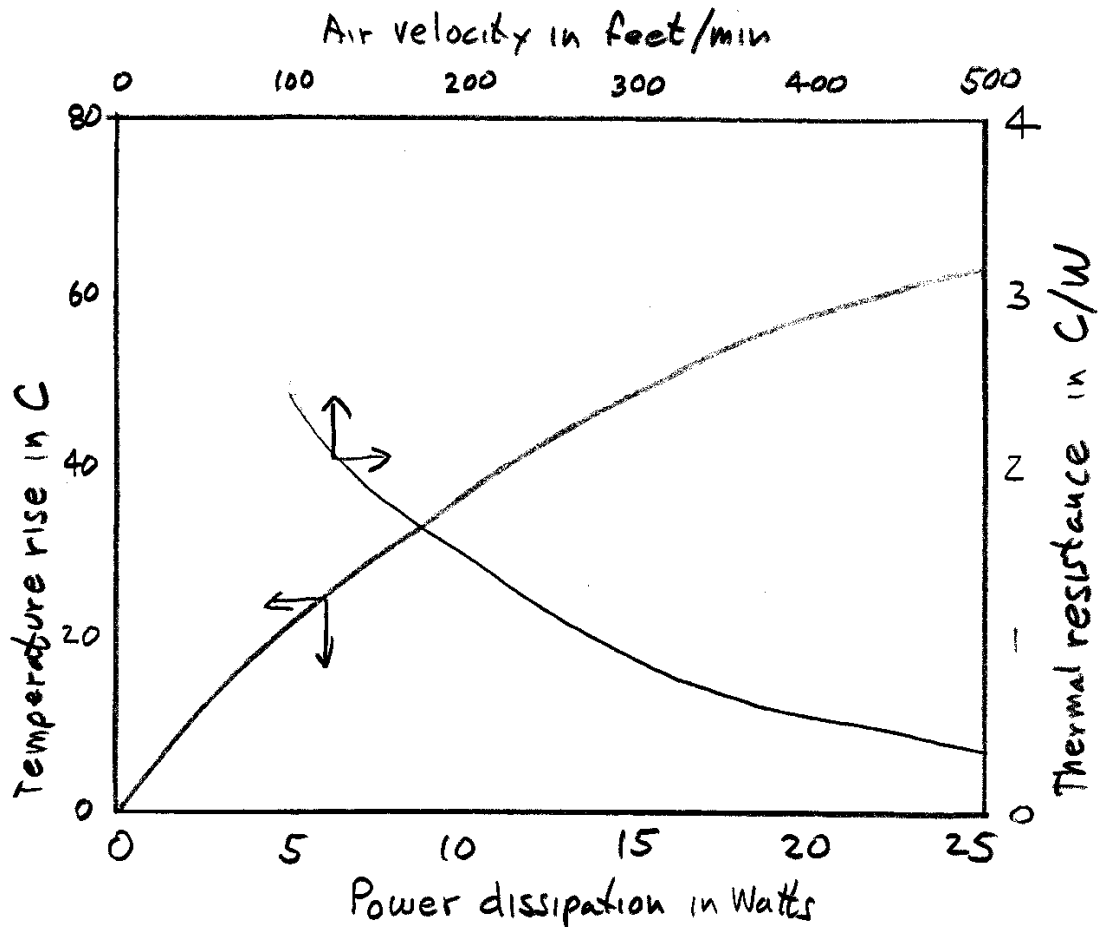


Figure 2: Typical heatsink data

The following is the proper method to use in selecting a heat sink.

1. Calculate the maximum power dissipation, P_d , that will occur in your device.
2. Lookup the maximum allowable internal temperature (i.e. junction temperature for solid state devices) in the data book.
3. Lookup the thermal resistance, θ_{jc} , from the internal device to the case.
4. Specify the actual maximum internal temperature you want to design to, T_{jmax} . This can be equal to that in the previous step but for long device life the maximum temperature should be many tens of degrees lower.
5. Calculate the maximum allowable case temperature by $T_{cmax} = T_{jmax} - P_d * \theta_{jc}$.
6. Specify the maximum ambient air temperature that the device must operate in, T_{amax} .
7. If the application is for natural convection then calculate the maximum allowable temperature rise of the heat sink: $T_{rmax} = T_{amax} - T_{cmax}$. If this number is small (less than about 10 degrees) then it may be very difficult to accomplish heat

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removal. It is impossible if the result is negative. If the application for forced air then calculate the maximum allowable thermal resistance of the heat sink:

$$\theta_{samax} = (T_{jmax} - T_{amax})/P_{dmax} - \theta_{jc}$$

8. Choose a heat sink that will physically mount to your device and that has a temperature rise or thermal resistance (as shown on a plot) for your operating P_d and expected air flow (from convection to forced) less than T_{rmax} or θ_{samax} . When in doubt, choose the larger heat sink.

The effective thermal resistance of the heat sink can be calculated as $\theta_{sa} = T_{rise} / P_d$. The T_{rise} is taken from the performance plot. Notice that the effective thermal resistance can vary a lot depending on how the heat sink is used. This is why the manufacture provides a plot rather than a specific value.

When forced air is a requirement then there needs to be some means for detecting either that the air flow is insufficient or the temperature of the case has exceeded some specification so that that some kind of shut down can take place to prevent failure.