

24. Conduction Cooling for Chassis and Circuit Boards

24.1 Introduction

Conduction cooling is important method used in many practical electronic systems such as spacecraft system as shown in Figure 24.1.

The heat is generated in active components whenever the electronic system is in operation. As the heat is generated, the temperature of the component increases and heat attempts to flow through any path it can find. If the heat source is constant, the temperature within the component continues to rise until the rate of the heat being generated is equal to the rate of the heat flowing away from the component. Steady state heat transfer then exists the heat flowing into the component is equal to the heat flowing away from the component.

Heat always flows from high temperature areas to low temperature areas. When the electronic system is operating, the electronic components are its hottest parts.

To control the hot spot component temperatures, the heat flow path must be controlled. If this is not done properly, the component temperatures are forced to rise in an attempt to balance the heat flow. Eventually, the temperatures may become so high that the component is destroyed if a protective circuit or a thermal cutoff switch is not used.

Conduction heat transfer in an electronic system is generally a slow process. Heat flow will not occur until a temperature difference has been established. This means that each member along the heat flow path must experience a temperature rise before the heat will flow to the next point along the path. This process continues until the final heat sink is reached, which is often the outside ambient air. This process may take many hours, perhaps even many days for a very large system, depending upon its size.

The materials along the heat flow path sharply influence the temperature gradients developed along the path. Heat can be conducted through any material: solid, liquid, or gas. The ability of the heat to flow through any material is determined by the physical properties of the material and by the geometry of the structure. The basic heat flow relation for steady state conduction from a single concentrated heat load is shown below in Equation.24.1.

$$Q = kA \frac{\Delta t}{L} \quad (24.1)$$

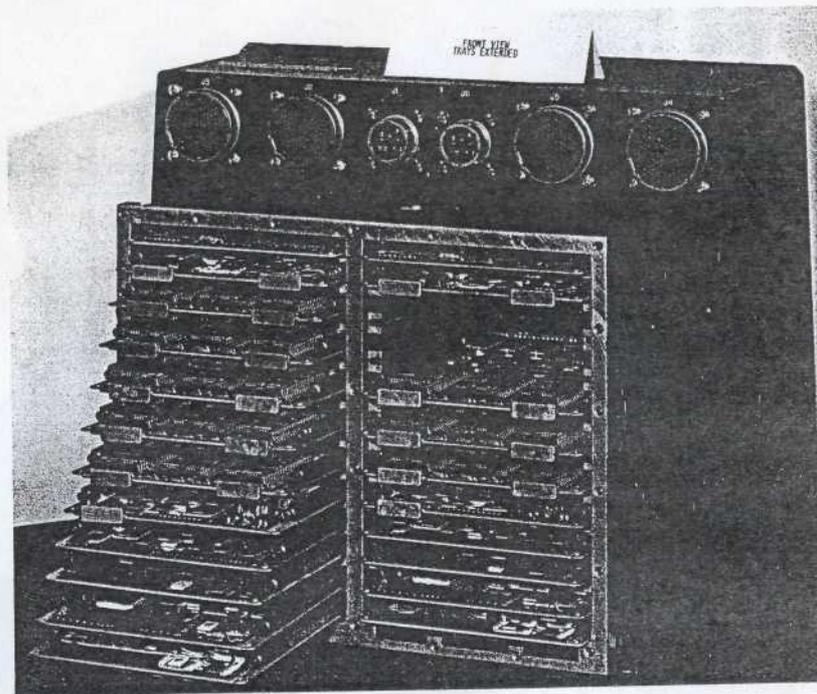


Figure 24.1 Conduction-cooled electronic box designed to carry the heat down the vertical walls to a base plate, for mounting in a spacecraft

24.2 Uniformly Distributed Heat Sources, Steady State Conduction

Identical electronic components are often placed next to one another, on circuit boards, as shown in Figure 24.2. When each component dissipates approximately the same amount of power, the result will be a uniformly distributed heat load.

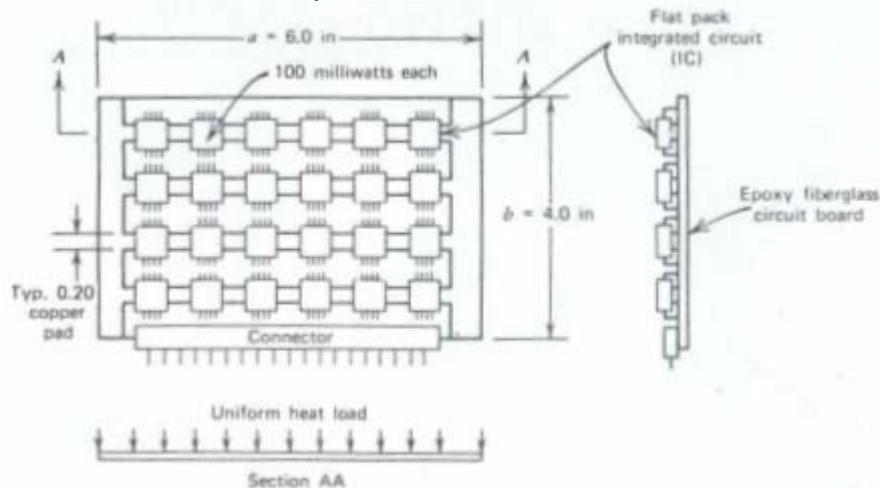


Figure 24.2 Printed circuit board with flat pack integrated circuits

When any one strip of electronic components is considered, as shown in section AA, the heat input can be evaluated as a uniformly distributed heat load. On a typical printed circuit board (PCB), the heat will flow from the component to the heat sink strip under the component, and then to the outer edges of the PCB, where it is removed. The heat sink strip is usually made of copper or aluminum, which have high thermal conductivity. The maximum temperature will occur at the center of the PCB and the minimum temperature

will occur at the edges. This produces a parabolic temperature distribution, as shown in Figure 24.3.

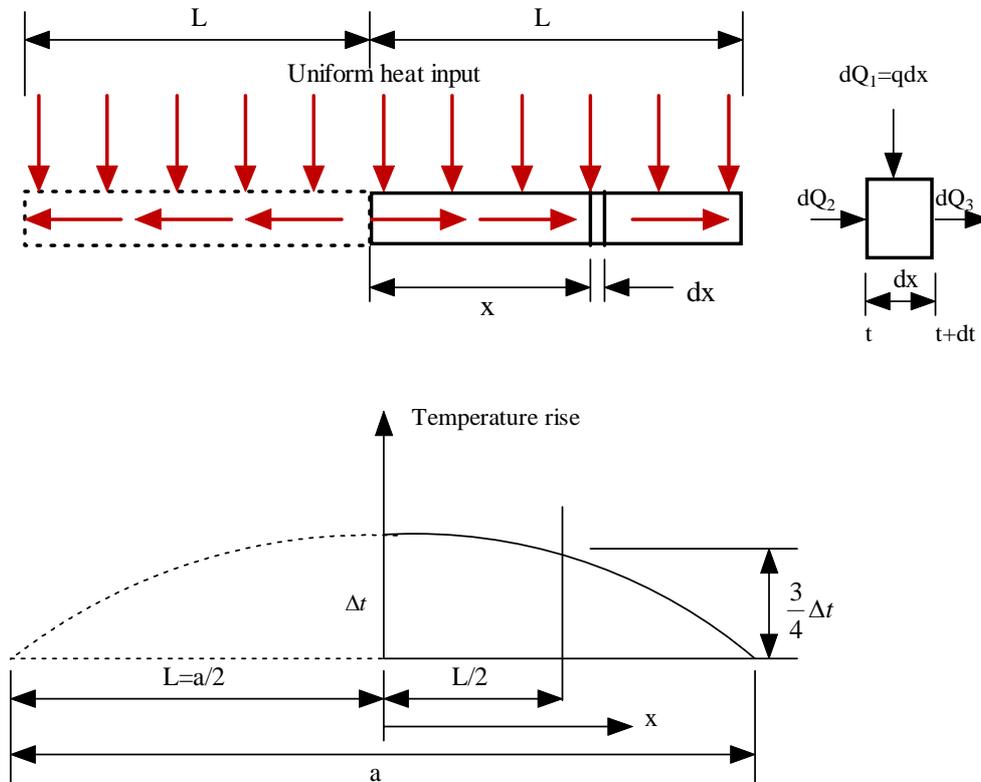


Figure 24.3 Parabolic temperature distributions for uniform heat load on a circuit board

When only one side of one strip is considered, a heat balance equation can be obtained by considering a small element dx of the strip, along the span with a length of L . Then

$$dQ_1 + dQ_2 = dQ_3$$

Where:

$$dQ_1 = qdx = \text{heat input}$$

$$dQ_2 = -kA \frac{dt}{dx} = \text{heat flow}$$

$$dQ_3 = -kA \frac{d(t+dt)}{dx} = \text{total heat}$$

Then

$$qdx - kA \frac{dt}{dx} = -kA \frac{dt}{dx} - kA \frac{d}{dx}(dt)$$

Then

$$\frac{d^2t}{dx^2} = -\frac{q}{kA}$$

This is a second-order differential equation, which can be solved by double integration. Integrating once yields to

$$\frac{dt}{dx} = -\frac{qx}{kA} + C_1$$

The second integrating yields to

$$t = -\frac{qx^2}{2kA} + C_1x + C_2$$

The constant C_1 is zero because at $x = 0$, the plate is adiabatic, and no heat is lost. The slope of the temperature gradient is therefore zero.

The constant C_2 is determined by letting the temperature at the end of the plate be t_e ; Then

$$\frac{qL^2}{2kA} + t_e = C_2$$

The temperature at any point along the plate (or strip) is

$$\begin{aligned} t &= -\frac{qx^2}{2kA} + \frac{qL^2}{2kA} + t_e \\ &= \frac{q}{2kA}(L^2 - x^2) + t_e \end{aligned} \quad (24.2)$$

This equation produces the parabolic shape for the temperature distribution; which is shown in Figure 24.3.

When $x = 0$. This results in the equation for the maximum temperature rise in a strip with a uniformly distributed heat load.

$$\Delta t = \frac{qL^2}{2kA}$$

The total heat input along the length L is

$$Q = qL$$

Then

$$\Delta t = \frac{QL}{2kA} \quad (24.3)$$

When the temperature rise at the midpoint along the heat sink strip of length L is desired, then $x = L/2$ Substituting this value into Equation.24.2. Will result in the temperature rise at the midpoint of the strip.

$$\text{midpoint } \Delta t = \frac{3qL^2}{8kA}$$

Considering only the strip with a length of L , the ratio of the strip midpoint temperature rise to the maximum temperature rise is shown in the following relation:

$$\frac{\text{midpoint } \Delta t}{\text{maximum } \Delta t} = \frac{3qL^2}{8kA} / \frac{qL^2}{2kA} = \frac{3}{4}$$

Example 24.1: A series of flat pack integrated circuits are to be mounted on a multilayer printed circuit board (PCB) as shown in Figure 24.2. Each flat pack dissipates 100 milliwatts of power. Heat from the components is to be removed by conduction through the printed circuit copper pads, which have 2 ounces of copper [thickness is 0.0028 in (0.0071 cm)]. The heat must be conducted to the edges of the PCB, where it flows into a heat sink. Determine the temperature rise from the center of the PCB to the edge to see if the design will be satisfactory.

Note that the typical maximum allowable case temperature is about 212 °F.

Solution:

The flat packs generate a uniformly distributed heat load, which results in the parabolic temperature distribution shown in Figure 24.4. Because of symmetry, only one half of the system is evaluated. Equation 24.3 is used to determine the temperature rise from the center of the PCB to the edge for one strip of components.

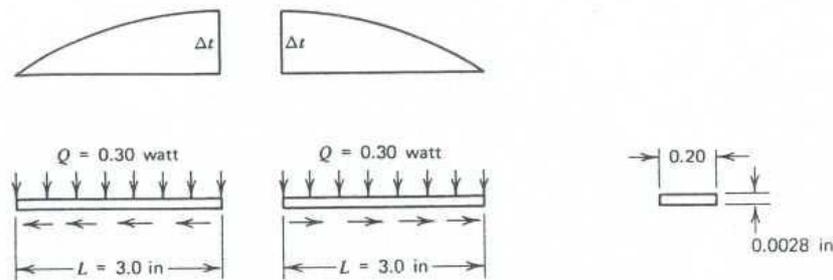


Figure 24.4 Uniformly distributed heat load on one copper strip

$Q = 3(0.1) = 0.3$ Watt heat input, one half strip

$L = 3$ in = 7.62 cm (length)

$k = 345$ W/m.K

$A = (0.2)(0.0028) = 0.00056$ in² = 0.00361 cm² (cross-sectional area)

Substitute into Equation 24.3 to obtain the temperature rise from the center of the PCB to the edge.

$$\Delta t = \frac{(0.3)(0.0762)10000}{2(345)(0.00361)} = 91.7 \text{ } ^\circ\text{C} = 197 \text{ } ^\circ\text{F}$$

The amount of heat that can be removed by radiation or convection for this type of system is very small. The temperature rise is therefore too high. By the time the sink temperature is added, assuming that it is 80°F, the case temperature on the component will be 277 °F. Since the typical maximum allowable case temperature is about 212 °F, the design is not acceptable.

If the copper thickness is doubled to 4 ounces, which has a thickness of 0.0056 in (0.014 cm), the temperature rise will be 114.5 °F (45.85 °C) then the case temperature on the component will be about 195 °F so that the system can be operated safely.

For high-temperature applications, the copper thickness will have to be increased to about 0.0112 in (0.0284 cm) for a good design.

24.3 Chassis with Nonuniform Wall Sections

Electronic chassis always seem to require cutouts, notches, and clearance holes for assembly access, wire harnesses, or maintenance. These openings will generally cut through a bulkhead or other structural member, which is required to carry heat away from some critical high-power electronic component. The cutouts result in nonuniform wall sections, which must be analyzed to determine their heat flow capability.

One convenient method for analyzing nonuniform wall sections is to subdivide them into smaller units that have relatively uniform sections. The heat flow path through each of the smaller, relatively uniform sections can then be defined in terms of a thermal resistance. This will result in a thermal analog resistor network, or mathematical model, which describes the thermal characteristics of that structural section of the electronic system.

The basic conduction heat flow relation shown by Equation. 24.1 can be modified slightly to utilize the thermal resistance concept. The thermal resistance for conduction heat flow is then defined by Equation. 24.4.

$$R = \frac{L}{kA} \quad (24.4)$$

Substituting this value into Equation 24.1 results in the temperature rise relation when the thermal resistance concept is used as shown in Equation 24.5

$$Q = \frac{\Delta t}{R} \quad (24.5)$$

The thermal resistance concept is very convenient for developing mathematical models of simple or complex electronic boxes. Analog resistor networks can be established for heat flow in one, two, and three dimensions with little effort. Complex shapes can often be modeled with many simple thermal resistors to provide an effective means for determining the temperature profile for almost any type of system.

Two basic resistance patterns, series and parallel, are used to generate analog resistor networks. A simple series pattern network is shown in Figure 24.5.

The total effective resistance (R_t) for the series flow network is determined by adding all the individual resistances, as shown in Equation. 24.6.



Figure 24.5 Series flow resistor network.

$$R_t = R_1 + R_2 + R_3 \dots \dots \dots \quad (24.6)$$

A simple parallel flow resistor network is shown in Figure 24.6.

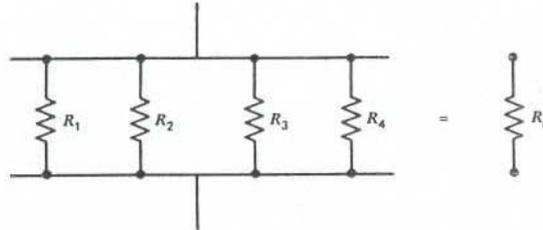


Figure 24.6 Parallel flow resistor network.

The total effective resistance for the parallel flow network is determined by combining the individual resistances as shown in Equation. 24.7.

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots \dots \dots \quad (24.7)$$

A typical electronic system will normally consist of many different combinations of series and parallel flow resistor networks.

Example 24.2: An aluminum (5052) plate is used to support a row of six power resistors. Each resistor dissipates 1.5 watts, for a total power dissipation of 9 watts. The bulkhead conducts the heat to the opposite wall of the chassis, which is cooled by a multiple fin heat exchanger. The bulkhead has two cutouts for connectors to pass through, as shown in Figure 24.7. Determine the temperature rise across the length of the bulkhead.

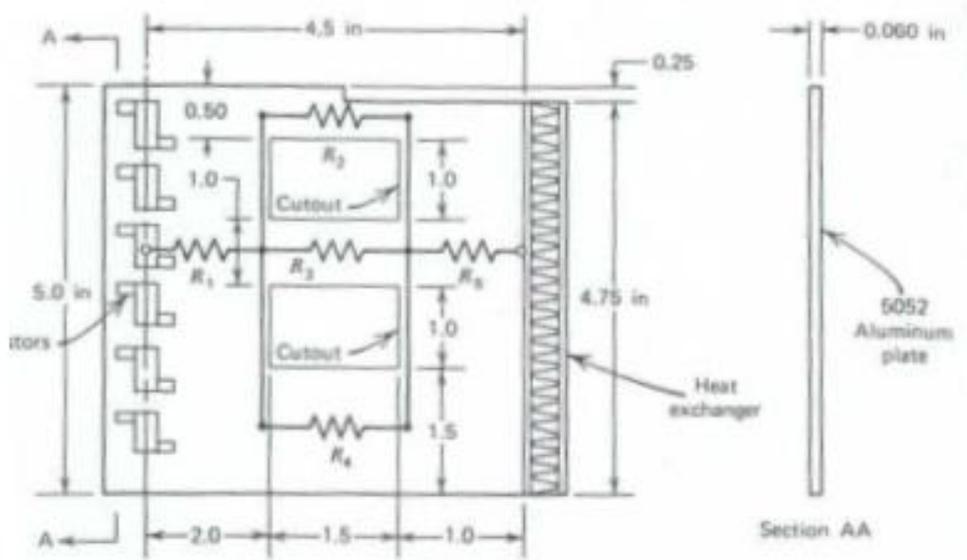


Figure 24.7 Bulkheads with two cutouts for connectors

Solution:

A mathematical model with series and parallel thermal resistor networks can be established to represent the heat flow path, as shown in Figure 24.8a.

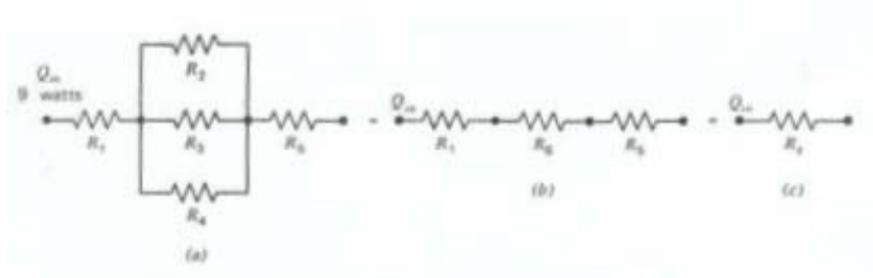


Figure 24.8 Bulkhead thermal models using a series and a parallel resistor network.

Firstly must determine the values of each resistor.

Determine resistor R_1 :

$$L_1 = 2 \text{ in} = 5.08 \text{ cm}$$

$$k_1 = 158 \text{ W/m.K}$$

$$A_1 = (5) (0.06) = 0.3 \text{ in}^2 = 1.935 \text{ cm}^2$$

$$R_1 = \frac{(0.0508)10000}{(1.935)(158)} = 1.6616 \text{ }^\circ\text{C/W}$$

Determine resistor R_2 :

$$L_2 = 1.5 \text{ in} = 3.81 \text{ cm}$$

$$K_2 = 158 \text{ W/m.K}$$

$$A_2 = (0.375) (0.06) = 0.0225 \text{ in}^2 = 0.145 \text{ cm}^2 \text{ (average area)}$$

$$R_2 = \frac{(0.0381)10000}{(0.145)(158)} = 16.63 \text{ }^\circ\text{C/W}$$

Determine resistor R_3 :

$$L_3 = 1.5 \text{ in} = 3.81 \text{ cm}$$

$$K_3 = 158 \text{ W/m.K}$$

$$A_3 = (1) (0.06) = 0.06 \text{ in}^2 = 0.387 \text{ cm}^2$$

$$R_3 = \frac{(0.0381)10000}{(0.387)(158)} = 6.23 \text{ }^\circ\text{C/W}$$

Determine resistor R_4 :

$$L_4 = 1.5 \text{ in} = 3.81 \text{ cm}$$

$$K_4 = 158 \text{ W/m.K}$$

$$A_4 = (1.5) (0.06) = 0.09 \text{ in}^2 = 0.581 \text{ cm}^2$$

$$R_4 = \frac{(0.0381)10000}{(0.581)(158)} = 4.15 \text{ }^\circ\text{C/W}$$

Determine resistor R_5 :

$$L_5 = 1 \text{ in} = 2.54 \text{ cm}$$

$$K_5 = 237 \text{ W/m.K}$$

$$A_5 = (4.75) (0.06) = 0.285 \text{ in}^2 = 1.839 \text{ cm}^2$$

$$R_5 = \frac{(0.0254)10000}{(1.839)(158)} = 0.874 \text{ } ^\circ\text{C/W}$$

After getting all resistors we can simplify the network from Figure 24.8a to as shown in Figure 24.8b. Where resistors R_2 , R_3 and R_4 are in parallel, which results in resistor R_6 .

$$\frac{1}{R_6} = \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}$$

$$R_6 = 2.166 \text{ } ^\circ\text{C/W}$$

The total thermal resistance is.

$$R_t = R_1 + R_6 + R_5 = 4.7 \text{ } ^\circ\text{C/W}$$

The temperature rise across the length of the bulkhead is then determined from Equation 24.5.

$$\Delta t = (9)(4.7) = 42.3 \text{ } ^\circ\text{C}$$

24.4 Circuit Board Edge Guides

Plug-in PCBs are often used with guides, which help to align the PCB connector with the chassis connector. These guides, which are usually fastened to the side walls of a chassis, grip the edges of the PCB as it is inserted and removed. If there is enough contact pressure and surface area at the interface between the edge guide and the PCB, the edge guide can be used to conduct heat away from the PCB. A typical installation is shown in Figure 24.9.

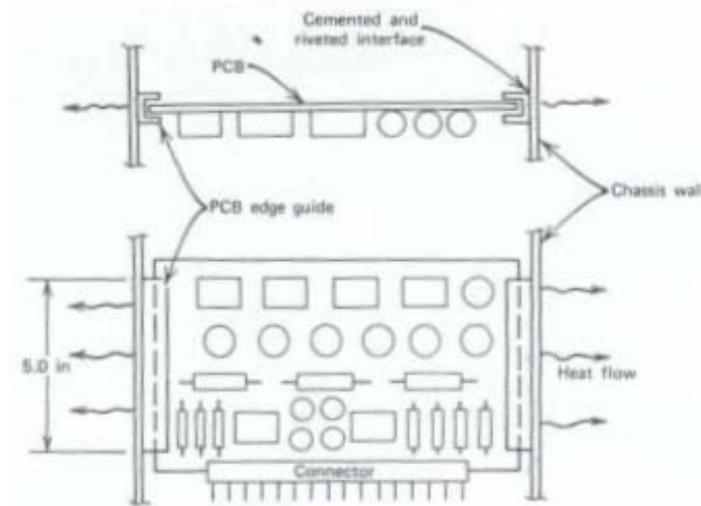


Figure 24.9 Plug-in PCB assembly with board edge guides

Plug-in PCBs must engage a blind connector, which is usually fastened to the chassis. If the chassis connector is rigid, with no floating provisions, the edge guide must provide that float, or many connector pins will be bent and broken. Rigid chassis connectors are generally used for electrical connections because wire-wrap harnesses, flex tape harnesses, and multilayer

master interconnecting mother boards are being used for production systems. These interconnections cannot withstand the excessive motion required for a floating connector system. Therefore, the floating mechanism is often built into the circuit board edge guides.

Many different types of circuit board edge guides are used by the electronics industry. The thermal resistance across a typical guide is rather difficult to calculate accurately, so that tests are used to establish these values. The units used to express the thermal resistance across an edge guide are °C in/watt. When the length of the guide is expressed in inches and the heat flow is in watts, the temperature rise is in degrees Celsius. Figure 24.10 shows four different types of edge guides, with the thermal resistance across each guide.

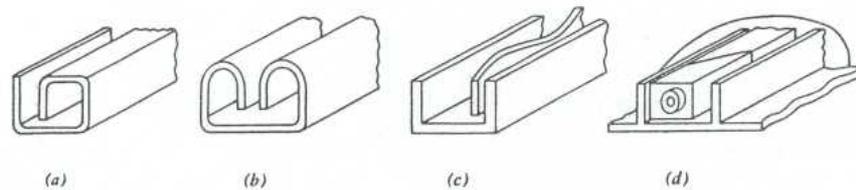


Figure 24.10 Board edge guides with typical thermal resistance, (a) G guide, 12°C in/watt; (b) B guide, 8°C in/watt; (c) U guide, 6°C in/watt; (d) wedge clamp, 2°C in/watt.

These board edge guides are generally satisfactory for applications at sea level or medium altitudes up to about 50,000 ft. At altitudes of 100,000 ft, test data show that the resistance values for the guides in Figure 24.10a-c will increase about 30%. The wedge clamp shown in Figure 24.10d will have about a 5% increase.

For hard-vacuum conditions, where the pressure is less than 10^{-6} torr (mm hg), as normally experienced in outer space work, some of these edge guides may not be satisfactory, except for very low power dissipations. Outer space environments generally require very high pressure interfaces, with fiat and smooth surfaces, to conduct heat effectively. Wedge clamps are very effective here because they can produce high interface pressures.

Example 24.3: Determine the temperature rise across the PCB edge guide (from the edge of the PCB to the chassis wall) for the assembly shown in Figure 24.9. The edge guide is 5.0 in long, type c, as shown in Figure 24.10. The total power dissipation of the PCB is 10 watts, uniformly distributed, and the equipment must operate at 100,000 ft.

Solution:

Since there are two edge guides, half of the total power will be conducted through each guide. The temperature rise at sea level conditions can be determined from Equation 24.8.

$$\Delta t = \frac{RQ}{L} \tag{24.8}$$

R= 6 °C in/watt (U guide)
 Q=10/2 =5 watt
 L= 5 in

$$\Delta t = \frac{(6)(5)}{5} = 6 \text{ }^{\circ}\text{C}$$

At altitude of 100,000 ft, the resistance across the edge guide will increase about 30%. The temperature rise at this altitude will then be.

$$\Delta t = 1.3(6) = 9 \text{ }^{\circ}\text{C}$$

24.5 Heat Conduction through Sheet Metal Covers

Lightweight electronic boxes often use sheet metal covers to enclose the chassis. Sometimes these covers are expected to conduct the heat away from the chassis for additional cooling. To effectively conduct heat from the chassis to the cover, a flat, smooth, high-pressure interface must be provided. The normal surface contact obtained at the interfaces of sheet metal members will not provide an effective heat conduction path. However, if a lip can be formed in the cover or on the sidewalls of the chassis, the heat conduction path can be substantially improved. Figure 24.11 shows how lips may be formed in the chassis and cover to improve the heat transfer across the interface.

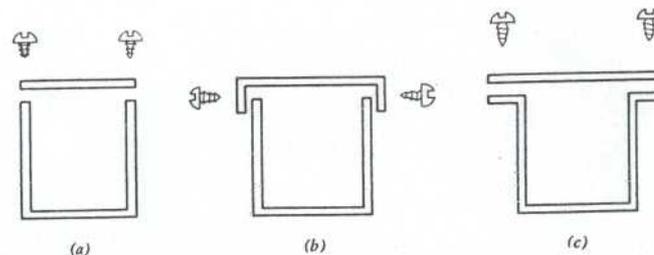


Figure 24.11 Different types of sheet metal covers on electronic boxes, (a) Poor; (b) good; (c) good.

24.6 Radial Heat Flow

Electronic support structures are not always rectangular in shape. If an electronic system is enclosed within a cylindrical structure, such as a small missile, it would be a waste of space to use a rectangular box for the electronics. The packaging form factor would probably conform to the natural cylindrical shape. Electronic components mounted on the inside surface of a cylindrical chassis would require a radial heat flow path to remove the heat when the heat sink is on the outer surface of the structure. The temperature rise from the inside surface to the outside surface of the cylindrical structure can be determined from Fourier's law as follow.

$$\begin{aligned} Q &= -kA \frac{dt}{dr} = \text{constant} \\ &= -k(2\pi Ra) \frac{dt}{dr} \end{aligned} \quad (24.9)$$

However, in a radial heat flow system, the cross-sectional area is constantly changing as the radius changes, as shown in Figure 24.12. So that we integrate the Equation 24.9, yields to

$$\begin{aligned}
 Q \int_{R_{in}}^{R_{out}} \frac{dR}{R} &= -2\pi k a \int_{t_{in}}^{t_{out}} dt \\
 Q &= \frac{2\pi k a (t_{in} - t_{out})}{\ln(R_{out} / R_{in})} \\
 &= \frac{\Delta t}{\frac{\ln(R_{out} / R_{in})}{2\pi k a}} \tag{24.10}
 \end{aligned}$$

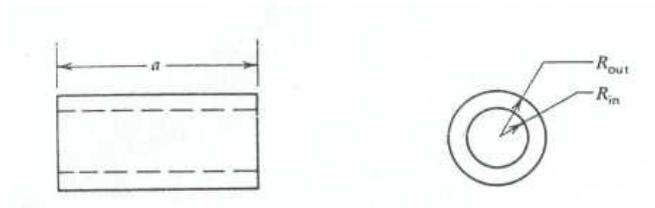


Figure 24.12 Hollow cylinder

Example 24.4: A hollow steel cylindrical shell has a group of resistors mounted on the inside surface, as shown in Figure 42.13. Heat is removed from the outside surface of the cylinder, so that the heat flow path is radial through the wall of the cylinder. Determine the temperature rise through the steel cylinder when the power dissipation is 10 watts.

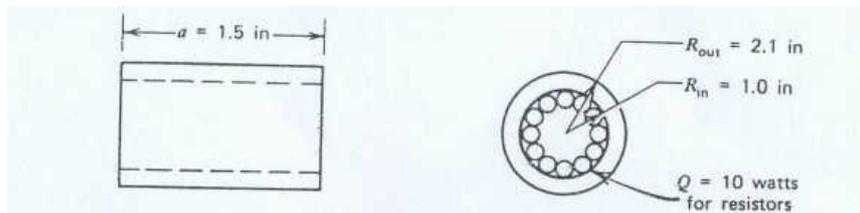


Figure 42.13 Resistors mounted on the inside wall of a hollow cylinder

Solution:

$R_{out} = 2.1 \text{ in} = 5.334 \text{ cm}$

$R_{in} = 1 \text{ in} = 2.54 \text{ cm}$

$a = 1.5 \text{ in} = 3.81 \text{ cm}$

$Q = 10 \text{ W}$

$k = 60.5 \text{ W/m.K}$

Substitute into Equation 24.10 for the temperature rise through the steel cylindrical wall.

$$10 = \frac{\Delta t}{\frac{\ln(2.1/1)}{2\pi(60.5)(0.0381)}}$$

Then

$\Delta t = 0.51 \text{ }^\circ\text{C}$