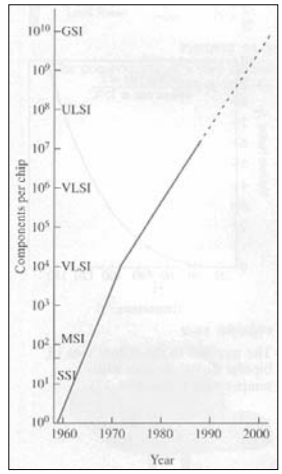
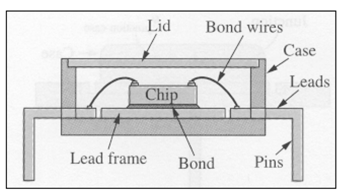
Why Cooling?

- The miniaturization of electronic systems has resulted in a dramatic increase in the amount of heat generated per unit volume.

- The failure rate of electronic devices increases almost ***<u>exponentially</u>*** with the operating temperature. The failure rate of electronic components is halved for each l0 °C reduction in their junction temperature.



Chip Carrier



- The chip is housed in a *chip carrier* or substrate made of ceramic, plastic, or glass in order to protect its delicate circuitry from the harmful environmental effects.
- It is also a strong housing for the safe handling of the chip during the manufacturing process.
- The junction-to-case thermal resistance depends on the *geometry* and the *size* of the chip and the chip carrier as well as the material properties of the *bonding* and the *case.*

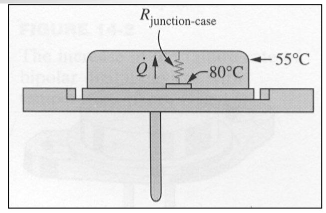
Example

Given:

Power input = 15 V

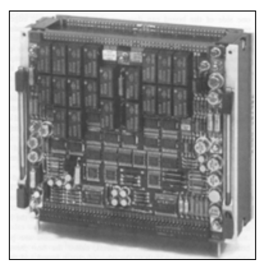
Current = 0.1 A

Find: Junction-to-case resistance.



Printed Circuit Board (PCB)

- A printed circuit board (PCB) is a properly wired plane board made of polymers and glass-epoxy materials on which various electronic components such as the ICs, diodes, transistors, resistors, and capacitors are mounted.

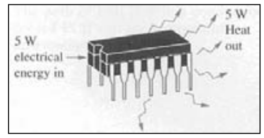


- A copper cladding is usually added on one or both sides of the board.
- The power dissipated by a PCB usually ranges from 5 to about 30 W.
- PCBs come in three types: *single-sided, double-sided,* and *multilayer* boards.

Cooling Load

- In the absence of other energy interactions, the heat output of an electric device in steady operation is equal to the power input to the device.

$$\dot{Q} = \dot{W}_e = VI = I^2R \quad (W)$$

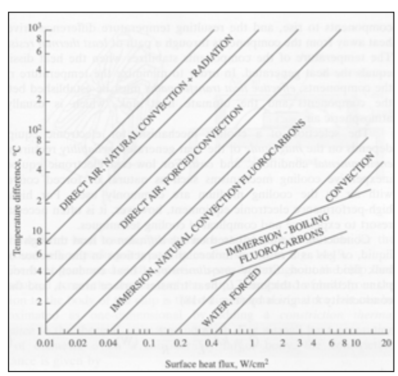


- It is common practice to inflate this number to leave some ***safety margin*** and to make some allowance for future growth (*e.g.* adding a fax/modem card to a PC).

- The actual power dissipated by a device can be considerably less than the rated power, depending on its ***duty cycle*** (the fraction of time it is on).

Cooling Load

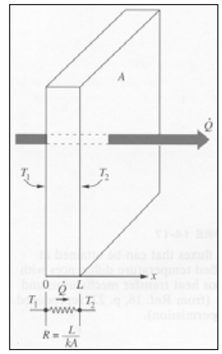
- The manufacturers of electronic devices usually specify the ***rate of heat dissipation*** and the ***maximum allowable component temperature*** for reliable operation.



- The selection of a cooling mechanism for electronic equipment depends on the ***magnitude*** of the heat generated, ***reliability*** requirements, ***environmental*** conditions, and ***cost.***

Conduction Cooling

- Conduction cooling is based on the *diffusion* of heat through a solid, liquid, or gas as a result of molecular interactions in the absence of any bulk fluid motion.



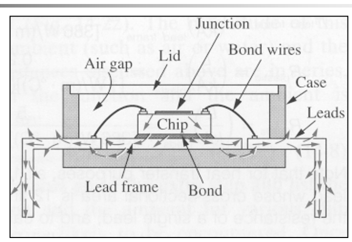
$$\dot{Q} = kA\frac{\Delta T}{L} = \frac{\Delta T}{R} \quad (W)$$

$$R = \frac{L}{kA} \quad (°C/W)$$

- When the rate of heat conduction Q is known, the temperature drop along a medium is simply determined from

$$\Delta T = \dot{Q}R \quad (°C)$$

Conduction in Chip Carriers



- For a small heat generation area of diameter *d* on a considerably larger body, the constriction resistance is given by

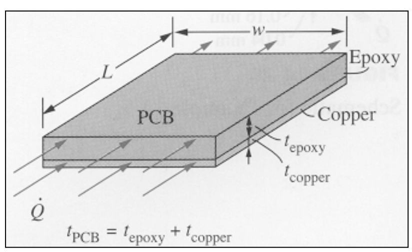
$$R_{constriction} = \frac{1}{2\sqrt{\pi}d\,k} \quad (°C/W)$$

Example

- A chip is dissipating 0.6 W of power in a DIP with 12 pin leads. If the temperature of the leads is 40°C, estimate the temperature at the junction of the chip.

Section and material	Thermal conductivity, W/(m · °C)	Thickness, mm	Heat transfer surface area
Junction constriction	—	—	diameter 0.4 mm
Silicon chip	120†	0.4	3 mm × 3 mm
Eutectic bond	296	0.03	3 mm × 3 mm
Copper lead frame	386	0.25	3 mm × 3 mm
Plastic separator	1	0.2	12 × 1 mm × 0.25 mm
Copper leads	386	5	12 × 1 mm × 0.25 mm

Conduction in PCBs



$$\dot{Q}_{PCB} = \dot{Q}_{epoxy} + \dot{Q}_{copper} = \left(kA\frac{\Delta T}{L}\right)_{epoxy} + \left(kA\frac{\Delta T}{L}\right)_{copper} = [(kt)_{epoxy} + (kt)_{copper}]\frac{w\Delta T}{L}$$

- The relative magnitudes of heat conduction along the two layers depends on the relative magnitudes of *k t* of the layers.

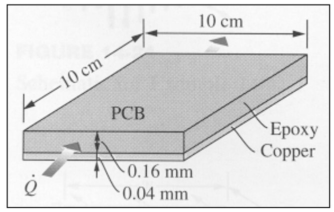
Effective thermal conductivity:

$$k_{eff} = \frac{(kt)_{epoxy} + (kt)_{copper}}{t_{epoxy} + t_{copper}} \quad [\text{W/(m} \cdot {}^\circ\text{C)}]$$

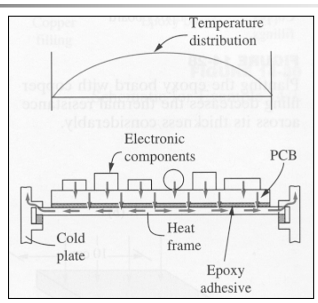
Example

Determine:

- Percentages of heat conduction along the copper [k = 386 W/(m.°C)], and epoxy [k = 0.26 W/(m.°C)] layers, and
- Effective thermal conductivity of the PCB.



Heat Frame



- Heat frames provide low-resistance path for the flow of heat from the circuit board to the heat sink.
- The thicker the heat frame, the lower the thermal resistance,
- When a heat frame is used, heat conduction in the epoxy layer of the PCB is through its *thickness* instead of along its length.

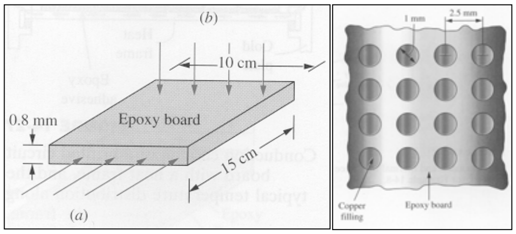
Example

Given:

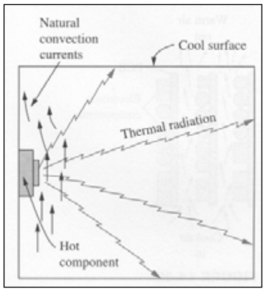
k_{eppoxy} = 0.26 W/(m.°C),
K_{copper} = 386 W/(m.°C)

Determine:

(1) Thermal resistance of epoxy layer along the 15-cm-long side,
(2) Across the laminate thickness.



Air Cooling: Natural Convection & Radiation



$$\dot{Q}_{conv} = h_{conv} A \Delta T = h_{conv} A (T_s - T_{fluid}) \quad (W)$$

$$\begin{cases} h_{conv} = K\left(\frac{\Delta T}{L}\right)^{0.25} & [W/(m^2.°C)] \\ h_{conv,P\,atm} = h_{conv,1atm}\sqrt{P} & [W/(m^2.°C)] \end{cases}$$

$$\dot{Q}_{rad} = \varepsilon A \sigma (T_s^4 - T_{surr}^4) \qquad (W)$$

Natural Convection (Simplified Correlations)

Geometry	W/m².°C
Vertical plate/cylinder	$h_{conv} = 1.42\left(\frac{\Delta T}{L}\right)^{0.25}$ L : height
Horizontal cylinder	$h_{conv} = 1.32\left(\frac{\Delta T}{D}\right)^{0.25}$ D : diameter
Horizontal plate (hot surface facing up)	$h_{conv} = 1.32\left(\frac{\Delta T}{L}\right)^{0.25}$ $L = \frac{4A}{P}$
Horizontal plate (hot surface facing down)	$h_{conv} = 0.59\left(\frac{\Delta T}{L}\right)^{0.25}$ $L = \frac{4A}{P}$
Components on a circuit board	$h_{conv} = 2.44\left(\frac{\Delta T}{L}\right)^{0.25}$
Small components or wires in free air	$h_{conv} = 3.53\left(\frac{\Delta T}{L}\right)^{0.25}$ L : height
Sphere	$h_{conv} = 1.92\left(\frac{\Delta T}{D}\right)^{0.25}$ D : diameter

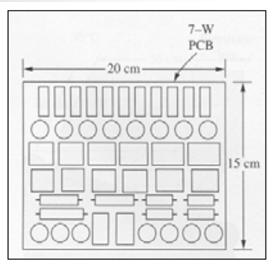
Example

Given:

Maximum allowable surface temperature = 100 °C.

Determine:

Maximum temperature of the environment in which this PCB can operate safely (a) at sea level, (b) at a location at 4000 m altitude where the atmospheric pressure is 61.66 kPa.

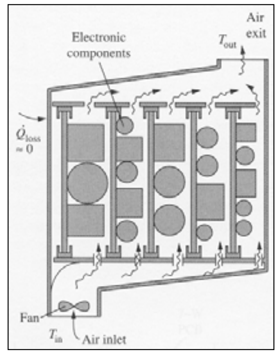


Air Cooling: Forced Convection

$$\dot{Q} = \dot{m} C_P (T_{out} - T_{in}) \quad (W)$$

where

$$\begin{cases} \dot{Q} & \text{Rate of heat transfer to the air (W)}, \\ \dot{m} & \text{Mass flow rate of air (kg/s)}, \\ C_p & \text{Specific heat of air (J/kg.°C)}, \\ T_{in} & \text{Average inlet temperature (°C)}, \\ T_{out} & \text{Average exit temperature (°C)}. \end{cases}$$



- It is considered a good design practice to limit the temperature rise of air to 10 °C, and the maximum exit temperature of air to 70 °C. In a properly designed forced air-cooled system, this results in a maximum component surface temperature of under 100°C.

Forced Convection Cooling: ***Guidelines***

- Check to see if *natural convection* cooling is adequate.
- If the temperature rise of air due to the power consumed by the motor of the fan is acceptable, mount the fan at the *inlet* of the box.
- Position and size the air exit vents so that there is *adequate air flow* throughout the entire box.
- Place the most critical electronic components near the *entrance,* where the air is coolest.
- Consider the effect of *altitude* in high-altitude applications.
- Try to avoid any unnecessary corners, sharp turns, and very high velocities (greater than 7 m/s), since the flow resistance is nearly proportional to the flow rate.
- Arrange the system such that *natural convection* helps forced convection.
- Fans mounted in *series* are best suited for systems with a high flow resistance. *Parallel* fans increase the flow rate of air, and are best suited for systems with small flow resistance.

Example

Given:

$\Delta T_{air,max}$ = 10 °C,

Determine:

- Flow rate of the air the fan needs to deliver,
- Fraction of the temperature rise of air due to the fan,
- The highest allowable inlet air temperature if the surface temperature of the components is not to exceed 90°C anywhere in the system.