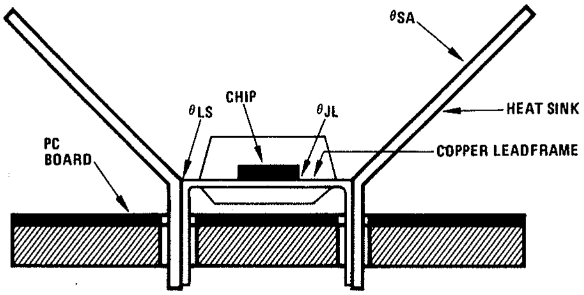
Re: AUDIO/RADIO HANDBOOK, NSC 1980

4.14.1 Heat Flow

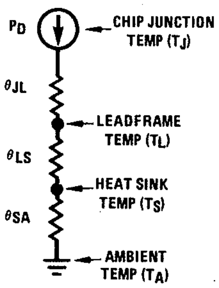
Heat can be transferred from the IC package by three methods, as described and characterized in Table 4.14.1.

TABLE 4.14.1 Methods of Heat Flow

METHOD	DESCRIBING PARAMETERS
Conduction is the heat transfer method most effective in moving heat from junction to case and case to heat sink.	Thermal resistance θ_{JL} and θ_{LS}. Cross section, length and temperature difference across the conducting medium.
Convection is the effective method of heat transfer from case to ambient and heat sink to ambient.	Thermal resistance θ_{SA} and θ_{LA}. Surface condition, type of convecting fluid, velocity and character of the fluid flow (e.g., turbulent or laminar), and temperature difference between surface and fluid.
Radiation is important in transferring heat from cooling fins.	Surface emissivity and area. Temperature difference between radiating and adjacent objects or space. See Table 4.14.2 for values of emissivity.



(a) Mechanical Diagram



(b) Electrical Equivalent

Symbols and Definitions

θ = Thermal Resistance (°C/W)
θ_{JL} = Junction to Leadframe
θ_{LS} = Leadframe to Heat Sink
θ_{SA} = Heat Sink to Ambient
θ_{JS} = Junction to Heat Sink = $\theta_{JL} + \theta_{LS}$
θ_{JA} = Junction to Ambient = $\theta_{JL} + \theta_{LS} + \theta_{SA}$
T_J = Junction Temperature (maximum) (°C)
T_A = Ambient Temperature
P_D = Power Dissipated (W)

(c) Symbols and Definitions

FIGURE 4.14.1 Heat Flow Model

4.14.2 Thermal Resistance

Thermal resistance is nothing more than a useful figure-of-merit for heat transfer. It is simply temperature drop divided by power dissipated, under steady state conditions. The units are usually °C/W and the symbol most used is θ_{AB}. (Subscripts denote heat flowing from A to B.)

The thermal resistance between two points of a conductive system is expressed as:

$$\theta_{12} = \frac{T_1 - T_2}{P_D} \,°\mathrm{C/W} \qquad (4.14.1)$$

4.14.3 Modeling Heat Flow

An analogy may be made between thermal characteristics and electrical characteristics which makes modeling straightforward:

T — temperature differential is analogous to V (voltage)
θ — thermal resistance is analogous to R (resistance)
P — power dissipated is analogous to I (current)

Observe that just as R = V/I, so is its analog θ = T/P. The model follows from this analog.

A simplified heat transfer circuit for a power IC and heat sink system is shown in Figure 4.14.1. The circuit is valid only if the system is in thermal equilibrium (constant heat flow) and there are, indeed, single specific temperatures T_J, T_L, and T_S (no temperature distribution in junction, case, or heat sink). Nevertheless, this is a reasonable approximation of actual performance.

4.14.4 Where to Find Parameters

P_D

Package dissipation is read directly from the "Power Dissipation vs. Power Output" curves that are found on all of the audio amp data sheets. Most data sheets provide separate curves for either 4, 8 or 16Ω loads. Figure 4.14.2 shows the 8Ω characteristics of the LM378.

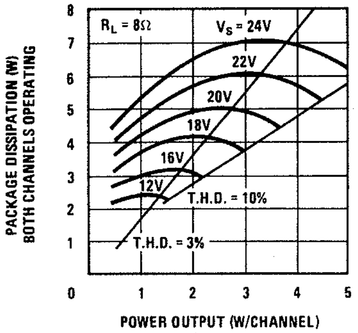


FIGURE 4.14.2 Power Dissipation vs. Power Output

> Note: For P_o = 2W and V_s = 18V, $P_{D(max)}$ = 4.1W, while the same P_o with V_s = 24V gives $P_{D(max)}$ = 6.5W – 50% greater! This point cannot be stressed too strongly: *For minimum P_D, V_s must be selected for the minimum value necessary to give the required power out.*

For loads other than those covered by the data sheet curves, max power dissipation may be calculated from Equation (4.14.2). (See Section 4.12.)

$$P_{D(max)} = \frac{V_S{}^2}{20\,R_L} \tag{4.14.2}$$

Equation (4.14.2) is for each channel when applied to duals.

When used for bridge configurations, package dissipation will be twice that found from Figure 4.14.2

θ_{LS}

The thermal resistance between lead frame and heat sink is a function of how close the bond can be made. For the D.I.P., soldering to the ground pins with 60/40 solder is recommended. When soldered, θ_{LS} may be neglected or a value of θ_{LS} = 0.25°C/W may be used. Where the package style permits bolting to the heat sink, θ_{LS} will depend on whether a heat sink compound and/or an insulating washer is used. For a TO-3 case style 0.1°C/W is obtained with compound, increasing to 0.4°C/W with a 3 mil mica washer. The TO-220 case style used by the LM383 has corresponding values for θ_{LS} between 1.6°C/W and 2.6°C/W.

$T_{J(max)}$

Maximum junction temperature for each device is 150°C.

θ_{JL}

Thermal resistance between junction to lead frame (or junction to heat sink if θ_{LS} is ignored) is read, directly from the "Maximum Dissipation vs. Ambient Temperature" curve found on the data sheet. Figure 4.14.3 shows a typical curve for the LM378.

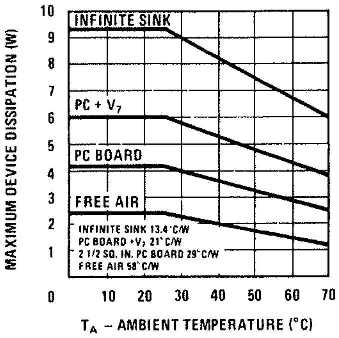


FIGURE 4.14.3 Maximum Dissipation vs. Ambient Temperature

> Note: θ_{JL} is the slope of the curve labeled "Infinite Sink." It is also $\theta_{JA(best)}$, while $\theta_{JA(worst)}$ is the slope of the "Free Air" curve, i.e., infinite heat sink and no heat sink respectively.

So, what does it mean? Simply that with no heat sink you can only dissipate

$$\frac{150°\text{C} - 25°\text{C}}{58°\text{C/W}} = 2.16\text{W}.$$

And with the best heat sink possible, the maximum dissipation is

$$\frac{150°\text{C} - 25°\text{C}}{13.4°\text{C/W}} = 9.33\text{W}$$

Or, for you formula lovers:

$$\text{Max Allowable } P_D = \frac{T_{J(max)} - T_A}{\theta_{JA}} \tag{4.14.3}$$

4.14.5 Procedure for Selecting Heat Sink

1. Determine $P_{D(max)}$ from curve or Equation (4.14.2).
2. Neglect θ_{LS} if soldering; if not, θ_{LS} must be considered.
3. Determine θ_{JL} from curve.
4. Calculate θ_{JA} from Equation (4.14.3)
5. Calculate θ_{SA} for necessary heat sink by subtracting (2) and (3) from (4) above, i.e., $\theta_{SA} = \theta_{JA} - \theta_{JL} - \theta_{LS}$ (4.14.4)

For example, calculate heat sink required for an LM378 used with V_s = 24V, R_L = 8Ω, P_o = 4W/channel and T_A = 25°C:

1. From Figure 4.14.2, P_D = 7W.
2. Heat sink will be soldered, so θ_{LS} is neglected.
3. From Figure 4.14.3, θ_{JL} = 13.4°C/W.
4. From Equation (4.14.3),

$$\theta_{JA} = \frac{150^\circ C - 25^\circ C}{7W} = 17.9^\circ C/W.$$

5. From Equation (4.14.4),

$$\theta_{SA} = 17.9^\circ C/W - 13.4^\circ C/W = 4.5^\circ C/W.$$

Therefore, a heat sink with a thermal resistance of 4.5°C/W is required. Examination of Figure 4.14.3 shows this to be substantial heatsinking, requiring forethought as to board space, sink cost, etc.

Results modeled:

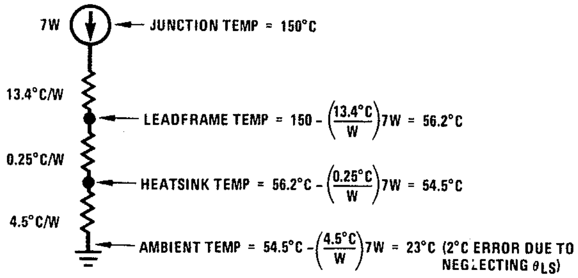


FIGURE 4.14.4 Heat Flow Model for LM378 Example

4.14.6 Custom Heat Sink Design

The required θ_{SA} was determined in Section 4.14.5. Even though many heat sinks are commercially available, it is sometimes more practical, more convenient, or more economical to mount the device to chassis, to an aluminum extrusion, or to a custom heat sink. In such cases, design a simple heat sink.

Simple Rules

1. Mount cooling fin vertically where practical for best conductive heat flow.
2. Anodize, oxidize, or paint the fin surface for better radiation heat flow; see Table 4.14.2 for emissivity data. However, note that although paint increases the emissivity of a surface, the paint itself has a high thermal resistance and should be removed where the semiconductor device is attached to the heat sink. (This will also apply to anodized and oxidized surfaces.)
3. Use 1/16″ or thicker fins to provide low thermal resistance at the IC mounting where total fin cross-section is least.

Fin Thermal Resistance

The heat sink-to-ambient thermal resistance of a vertically mounted symmetrical square or round fin (see Figure 4.4.5) in still air is:

$$\theta_{SA} = \frac{1}{2H^2\eta\,(h_C + h_r)}\ ^\circ C/W \qquad (4.14.5)$$

where: H = height of vertical plate in inches
η = fin effectiveness factor
h_C = convection heat transfer coefficient
h_r = radiation heat transfer coefficient

$$h_C = 2.21 \times 10^{-3}\left(\frac{T_S - T_A}{H}\right)^{1/4}\ W/in^2\,^\circ C \qquad (4.14.6)$$

$$h_r = 1.47 \times 10^{-10}\,E\left(\frac{T_S + T_A}{2} + 273\right)^3\ W/in^2\,^\circ C \qquad (4.14.7)$$

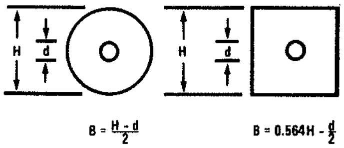
where: T_S = temperature of heat sink at IC mounting, in °C
T_A = ambient temperature in °C
E = surface emissivity (see Table 4.14.2)

Fin effectiveness factor η includes the effects of fin thickness, shape, thermal conduction, etc. It may be determined from the nomogram of Figure 4.14.6.

TABLE 4.14.2 Emissivity Values for Various Surface Treatments

SURFACE	EMISSIVITY, E
Polished Aluminum	0.05
Polished Copper	0.07
Rolled Sheet Steel	0.66
Oxidized Copper	0.70
Black Anodized Aluminum	0.7 - 0.9
Black Air Drying Enamel	0.85 - 0.91
Dark Varnish	0.89 - 0.93
Black Oil Paint	0.92 - 0.96

For untreated copper and aluminum surfaces, E can be approximated to about 0.2.



Note: For H >> d, using B = H/2 is a satisfactory approximation for either square or round fins.

FIGURE 4.14.5 Symmetrical Fin Shapes

The procedure for use of the nomogram of Figure 4.14.6 is as follows:

1. Specify fin height H as first approximation.
2. Calculate $h = h_r + h_C$ from Equations (4.14.6) and (4.14.7).
3. Determine α from values of h and fin thickness x (line a).
4. Determine η from values of B (from Figure 4.14.5) and α (line b).

The value of η thus determined is valid for vertically mounted symmetrical square or round fins (with $H \gg d$) in still air. For other conditions, η must be modified as follows:

Horizontal mounting — multiply h_C by 0.7.

Horizontal mounting where only one side is effective — multiply η by 0.5 and h_C by 0.94.

For 2:1 rectangular fins — multiply h by 0.8.

For non-symmetrical fins where the IC is mounted at the bottom of a vertical fin — multiply η by 0.7.

Fin Design

1. Establish initial conditions, T_A and desired θ_{SA} as determined in Section 4.14.5.
2. Determine T_S at contact point with the IC by rewriting Equation (4.14.1):

$$\theta_{JL} + \theta_{LS} = \frac{T_J - T_S}{P_D} \qquad (4.14.8)$$

$$T_S = T_J - (\theta_{JL} + \theta_{LS})(P_D) \qquad (4.14.9)$$

$$\approx T_J - \theta_{JL} P_D$$

3. Select fin thickness, x > 0.0625" and fin height, H.
4. Determine h_C and h_r from Equations (4.14.6) and (4.14.7).
5. Find fin effectiveness factor η from Figure 4.14.6.
6. Calculate θ_{SA} from Equation (4.14.5).
7. If θ_{SA} is too large or unnecessarily small, choose a different height and repeat steps (3) through (6).

Design Example

Design a symmetrical square vertical fin of 1/16" thick black anodized aluminum to be bolted onto an LM379 delivering a maximum power of 4W/Ch into 8Ω from a 28V supply.

1. LM379 operating conditions are:

   $T_J = 150°C_{(MAX)}$, $T_A = 55°C_{(MAX)}$

   From Figure 4.4.9, $\theta_{JL} = 6°C/W$

   From Figure 4.4.8, $P_{D(MAX)} = 9.5W$

2. From Equation 4.4.3

$$\theta_{JA} = \frac{150°C - 55°C}{9.5W} = 10°C/W$$

   From Equation 4.14.4 (neglect θ_{LS})

   $\theta_{SA} = 10°C - 6°C/W = 4°CC/W$

3. $T_S = 150°C - 6°C/W(9.5W) = 93°C$
4. X = 0.0625" from initial conditions

   E = 0.9 from Table 4.14.2.

   Select H = 3.5" for first trial (experience will simplify this step).

5. From Equation 4.14.6

$$h_C = 2.21 \times 10^{-3} \frac{93 - 60}{3.5}^{1/4}$$

$$= 3.87 \times 10^{-3} \text{ W/°C in}^2$$

   From Equation 4.14.7

$$h_r = 1.47 \times 10^{-10} \times 0.9 \frac{93 + 60 + 273}{2}^{3}$$

$$= 5.6 \times 10^{-3} \text{W/°C in}^2$$

$$h = h_r + h_C = 9.47 \times 10^{-3} \text{W/°C in}^2$$

6. From h and f_{in} thickness use Figure 4.14.6 to find α (line a)

   $\alpha = 0.24$

7. From Figure 4.14.5

   B = 1.91 inches

8. From Figure 4.14.6 (line b)

   $\eta = 0.85$

9. From Equation 4.14.5

$$\theta_{SA} = \frac{10^3}{2 \times 12.25 \times 0.85 \times 9.46} = 5.1°C/W$$

   Since the required heatsink thermal resistance is 4°C/W a larger f_{in} will be needed. A 4.25" square will increase the area by about 40% and a new calculation is made.

5'. $h_C = 3.7 \times 10^{-3} \text{W/°C in}^2$

$h_r = 5.6 \times 10^{-3} \text{W/°C in}^2$

$h = 9.3 \times 10^{-3} \text{W/°C in}^2$

6'. $\alpha = 0.24$

7'. B = 2.4

8'. $\eta = 0.73$

9'. $\theta_{SA} = 4.08°C/W$ which is satisfactory.

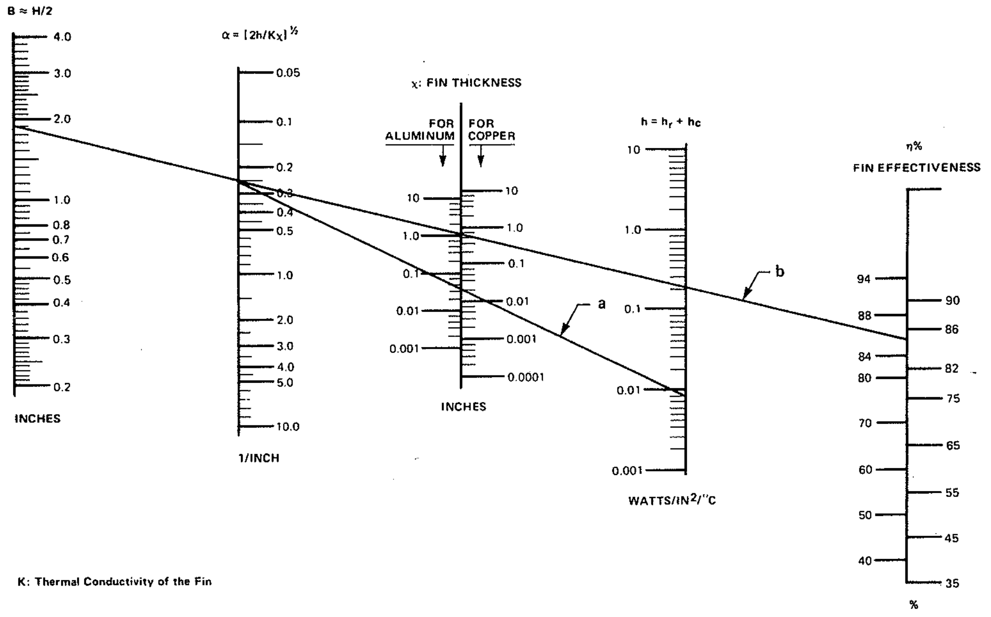


FIGURE 4.14.6 Fin Effectiveness Nomogram for Symmetrical, Flat, Uniformly-Thick, Vertically Mounted Fins

Although the above design procedure will specify the dimensions of the required heatsink, any design should be thoroughly tested under actual operating conditions to ensure that the maximum device case temperature does not exceed the rating for worst case thermal and load conditions.

4.14.7 Heatsinking with PC Board Foil

National Semiconductor's use of copper leadframes in packaging power ICs, where the center three pins on either side of the device are used for heatsinking, allows for economical heat sinks via the copper foil that exists on the printed circuit board. Adequate heatsinking may be obtained for many designs from single-sided boards constructed with 2 oz. copper. Other, more stringent, designs may require two-sided boards, where the top side is used entirely for heatsinking. Figure 4.14.7 allows easy design of PC board heat sinks once the desired thermal resistance has been calculated from Section 4.14.5.

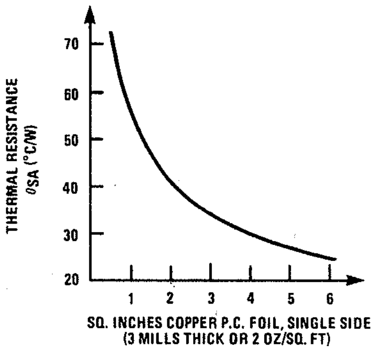


FIGURE 4.14.7 Thermal Resistance vs. Square Inches of Copper Foil