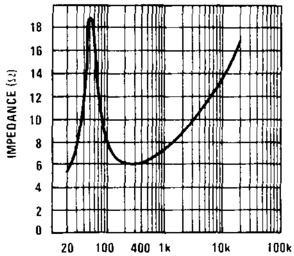
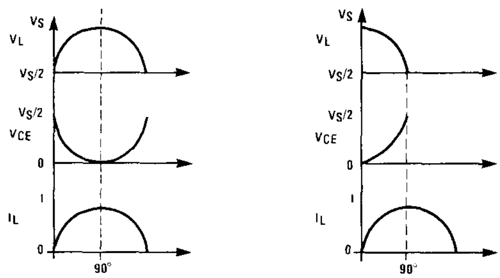


FIGURE 4.13.1 Impedance Curve for a Typical Dynamic Loudspeaker



Speaker Voltage and Current Phase Angle Equal to 0 Degrees
(a)

Speaker Voltage and Current Phase Angle Equal to 90 Degrees
(b)

FIGURE 4.13.2 Phase Angle Relationship Between Voltage and Current

difference Figure 4.13.2b results, where there exists zero volts across the load, maximum voltage across the package, and maximum current flowing through both, producing maximum package dissipation.

Returning to mathematics for a moment to derive a new expression containing phase angle and plotting the results produces the curve shown in Figure 4.13.3. The importance of Figure 4.13.3 is seen by comparing the power ratio at zero degrees (0.405) with that at 60 degrees (0.812) – double! This means that *the maximum package dissipation can be twice as much for a loudspeaker load as for a resistive load.* What softens this hard piece of reality is the relative rarity and short duration of amplifiers running at (or near)

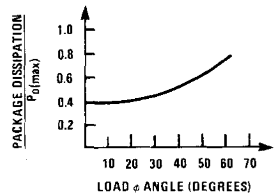


FIGURE 4.13.3 Class B Package Dissipation for Reactive Loads

maximum power output; also, most heat sinks have adequate thermal capacity to ride through these peaks. In any event, phase angle is real and it does increase power dissipation and needs to be considered in heat sink design.

4.14 HEATSINKING

Insufficient heatsinking accounts for many phone calls made to complain about power ICs not meeting published specs. This problem may be avoided by proper application of the material presented in this section. Heatsinking is not difficult, although the first time through it may seem confusing.

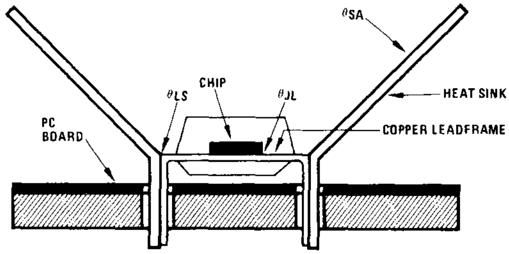
If testing a breadboarded power IC results in premature waveform clipping, or a "truncated shape," or a "melting down" of the positive peaks, the IC is probably in thermal shutdown and requires more heatsinking. The following information is provided to make proper heat sink selection easier and help take the "black magic" out of package power dissipation.

4.14.1 Heat Flow

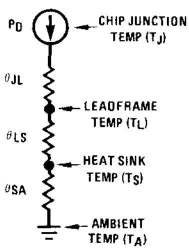
Heat can be transferred from the IC package by three methods, as described and characterized in Table 4.14.1.

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_{JC} and θ_{CS}. 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_{CA}. 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:

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

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.

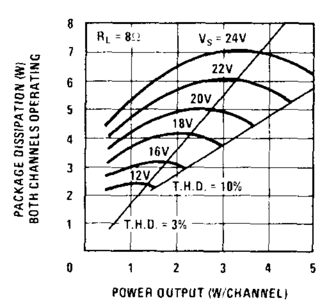


FIGURE 4.14.2 Power Dissipation vs. Power Output

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 (or four times Equation (4.14.2).*

θ_{LS}

Thermal resistance between lead frame and heatsink is a function of how close the bond can be made. The method recommended is use of 60/40 solder. When soldered, θ_{LS} may be neglected or a value of θ_{LS} = 0.25°C/W may be used.

$T_{J(max)}$

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.

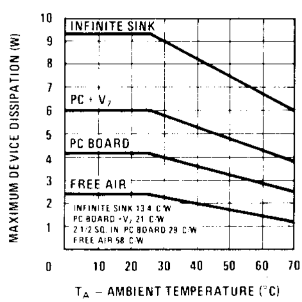


FIGURE 4.14.3 Maximum Dissipation vs. Ambient Temperature

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

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

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

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

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., $\theta_{SA} = \theta_{JA} - \theta_{JL} - \theta_{LS}$.

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),

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

5. From Equation (4.14.4),

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

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:

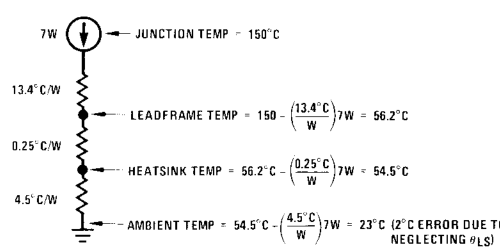


FIGURE 4.14.4 Heat Flow Model for LM378 Example

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 regulator 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.
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 (4.14.6)

h_r = radiation heat transfer coefficient (4.14.7)

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

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

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

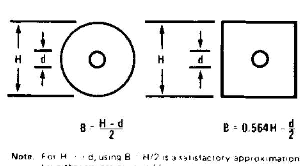


FIGURE 4.14.5 Symmetrical Fin Shapes

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 black anodized 1/16″ thick aluminum to have a thermal resistance of 4°C/W. LM379 operating conditions are:

1. $T_J = 150^\circ C$, $T_A = 60^\circ C$, $P_D = 9.5W$, $\theta_{JL} = 6^\circ C/W$, neglect θ_{LS}.
2. $T_S = 150^\circ C - 6^\circ C/W\,(9.5W) = 93^\circ C$.
3. 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).

4. $$h_C = 2.21 \times 10^{-3}\left(\frac{93 - 60}{3.5}\right)^{1/4}$$

$$= 3.86 \times 10^{-3} W/^\circ C\,in^2$$

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

4

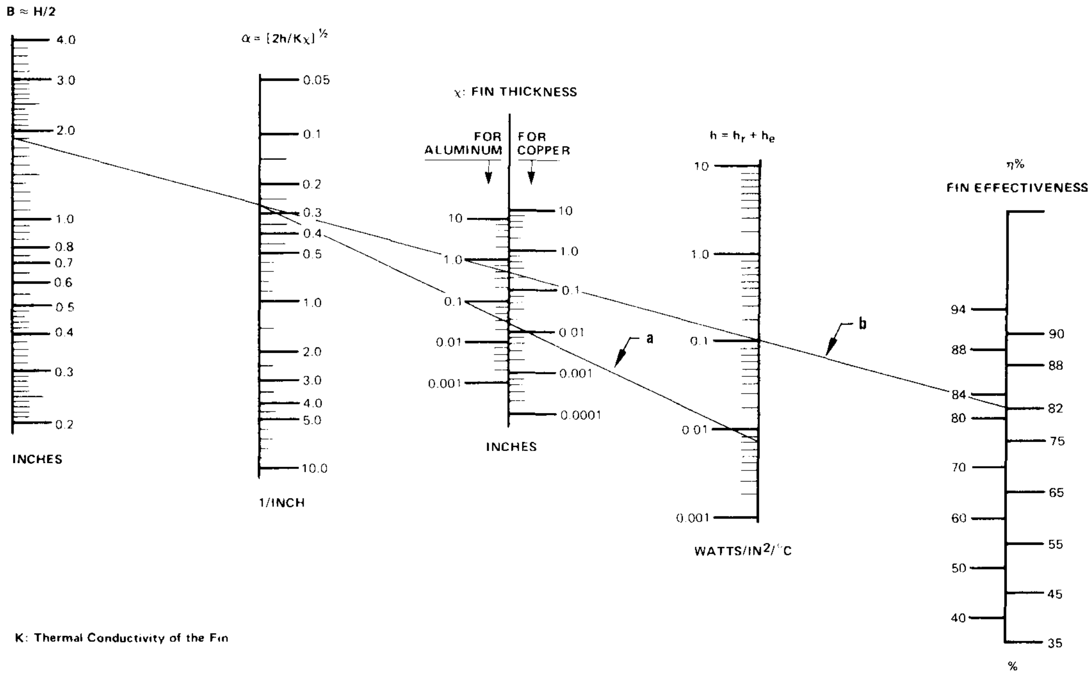


FIGURE 4.14.6 Fin Effectiveness Nomogram for Symmetrical, Flat, Uniformly-Thick, Vertically Mounted Fins

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

$h = h_c + h_r = 9.46 \times 10^{-3} W/^\circ C\,in^2$

5. $\eta = 0.84$ from figure 4.14.6.

6. $$\theta_{SA} = \frac{10^3}{2 \times 12.3 \times 0.84 \times 9.46} = 5.1^\circ C/W,$$

which is too large.

7. A larger fin is required, probably by about 40% in area. Accordingly, using a fin of 4.25" square, a new calculation is made.

4'. $$h_c = 2.21 \times 10^{-3}\left(\frac{33}{4.2}\right)^{1/4} = 3.7 \times 10^{-3}$$

$h_r = 5.6 \times 10^{-3}$ as before

$h = 9.3 \times 10^{-3}$

5'. $\eta = 0.75$ from Figure 4.14.6.

6. $$\theta_{SA} = \frac{10^3}{2 \times 18 \times 0.75 \times 9.3} = 3.98^\circ C/W,$$

which is satisfactory.

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.

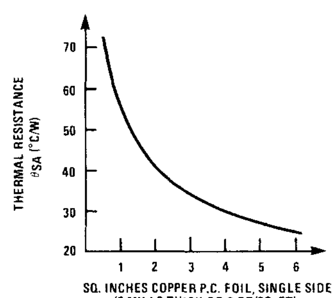


FIGURE 4.14.7 Thermal Resistance vs. Square Inches of Copper Foil