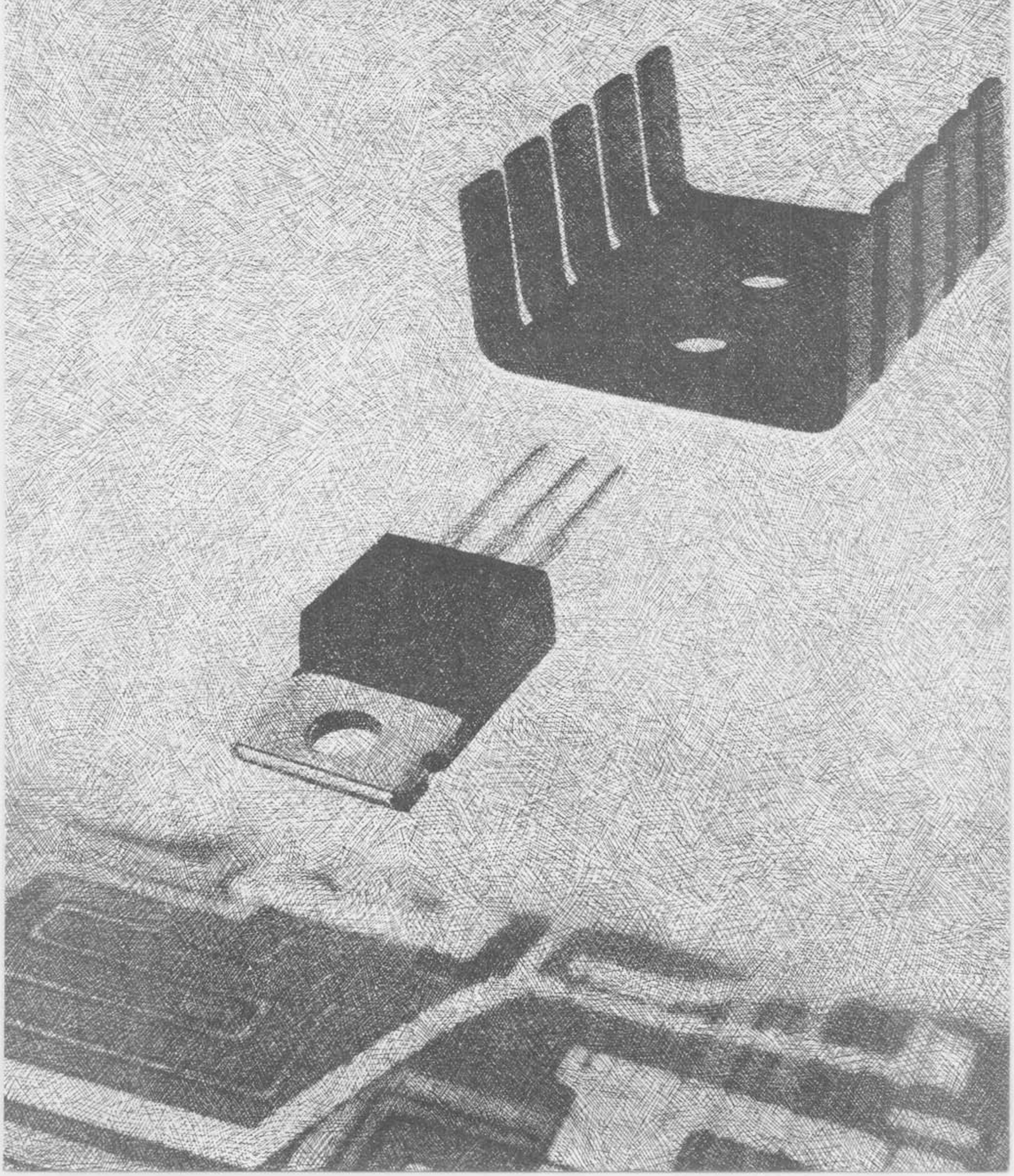
# Section 4.0
# Heat Flow & Thermal Resistance



# 4.0 HEAT FLOW & THERMAL RESISTANCE

## 4.1 HEAT FLOW

Heat can be transferred from the regulator package by three methods, as described and characterized in Table 4.1.

**TABLE 4.1. 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 $\theta_{JC}$ & $\theta_{CS}$. 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 $\theta_{SA}$ and $\theta_{CA}$. 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 4.2 for values of emissivity. |

## 4.2 THERMAL RESISTANCE

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

$$\theta_{12} = \frac{T_1 - T_2}{P_D} \,^\circ\text{C/W} \tag{4.1}$$

where subscript order indicates the direction of heat flow. A simplified heat transfer circuit for a cased semiconductor and heat sink system is shown in Figure 4.1. The circuit is valid only if the system is in thermal equilibrium (constant heat flow) and there are, indeed, single specific temperatures $T_J$, $T_C$, and $T_X$ (no temperature distribution in junction, case, or heat sink). Nevertheless, this is a reasonable approximation of actual performance.

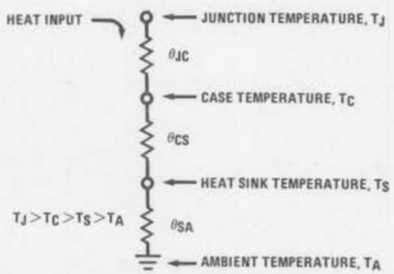



**FIGURE 4.1. Semiconductor-Heat Sink Thermal Circuit**

The junction-to-case thermal resistance $\theta_{JC}$ specified in the regulator data sheets depends upon the material and size of the package, die size and thickness, and quality of the die bond to the case or lead frame. The case-to-heat sink thermal resistance $\theta_{CS}$ depends on the mounting of the regulator to the heat sink and upon the area and quality of the contact surface. Typical $\theta_{CS}$ for several packages and mounting conditions are as shown in Table 4.2.

The heat sink to ambient thermal resistance $\theta_{SA}$ depends on the quality of the heat sink and the ambient conditions. A listing of approximate $\theta_{SA}$ for a number of commercially available heat sinks appears in Section 5. $\theta_{SA}$ includes effects of both convection and radiation.

## 4.3 BASIC THERMAL CALCULATIONS

Cooling is normally required to maintain the worst case operating junction temperature $T_J$ of the regulator below the specified maximum value $T_{J(MAX)}$. $T_J$ can be calculated from known operating conditions. Rewriting Eqn 4.1, we find

$$\theta_{JA} = \frac{T_J - T_A}{P_D} \,^\circ\text{C/W} \tag{4.2}$$

$$T_J = T_A + P_D \theta_{JA} \,^\circ\text{C} \tag{4.3}$$

Where: $P_D = (V_{IN} - V_{OUT})I_{OUT} + V_{IN} I_Q$

$\approx (V_{IN} - V_{OUT})I_{OUT}$

except for TO-92 package where $V_{IN} I_Q$ must be considered important.

$I_Q$ = Regulator quiescent current

$\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA}$.

Data sheets usually provide a plot of Eqn 4.3 for several heat sinks. An example for the LM340T with $T_J = T_{J(MAX)} = 150^\circ$C appears in Figure 4.2. Note that for the lower curve $\theta_{JA} = \theta_{CS} + \theta_{SA}$ while the upper curve is for $\theta_{JA} = \theta_{JC}$. Where the upper curve slope is zero, the limit is the arbitrary power dissipation rating instead of Eqn 4.1.

Table 4.2 Approximate Thermal Resistance, Case to Heat Sink $\theta_{CS}$ in °C/W

| Package | Direct contact | Contact with silicone grease | Contact with grease and mica washer |
|---|---|---|---|
| TO-3 | 0.5 - 0.7 | 0.3 - 0.5 | 0.4 - 0.6 |
| TO-202 | 1.5 - 2.0 | 0.9 - 1.2 | 1.2 - 1.7 |
| TO-220 | 1.0 - 1.3 | 0.6 - 0.8 | 0.8 - 1.1 |

Normally, we impose a full load operating junction temperature $T_J$ at 25°C (or more) below specified $T_{J(MAX)}$ at maximum expected $T_A$, and we need to find the required $\theta_{JA}$ from Eqn 4.2.

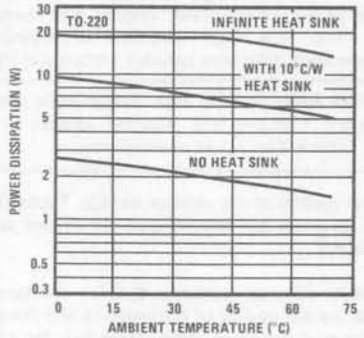
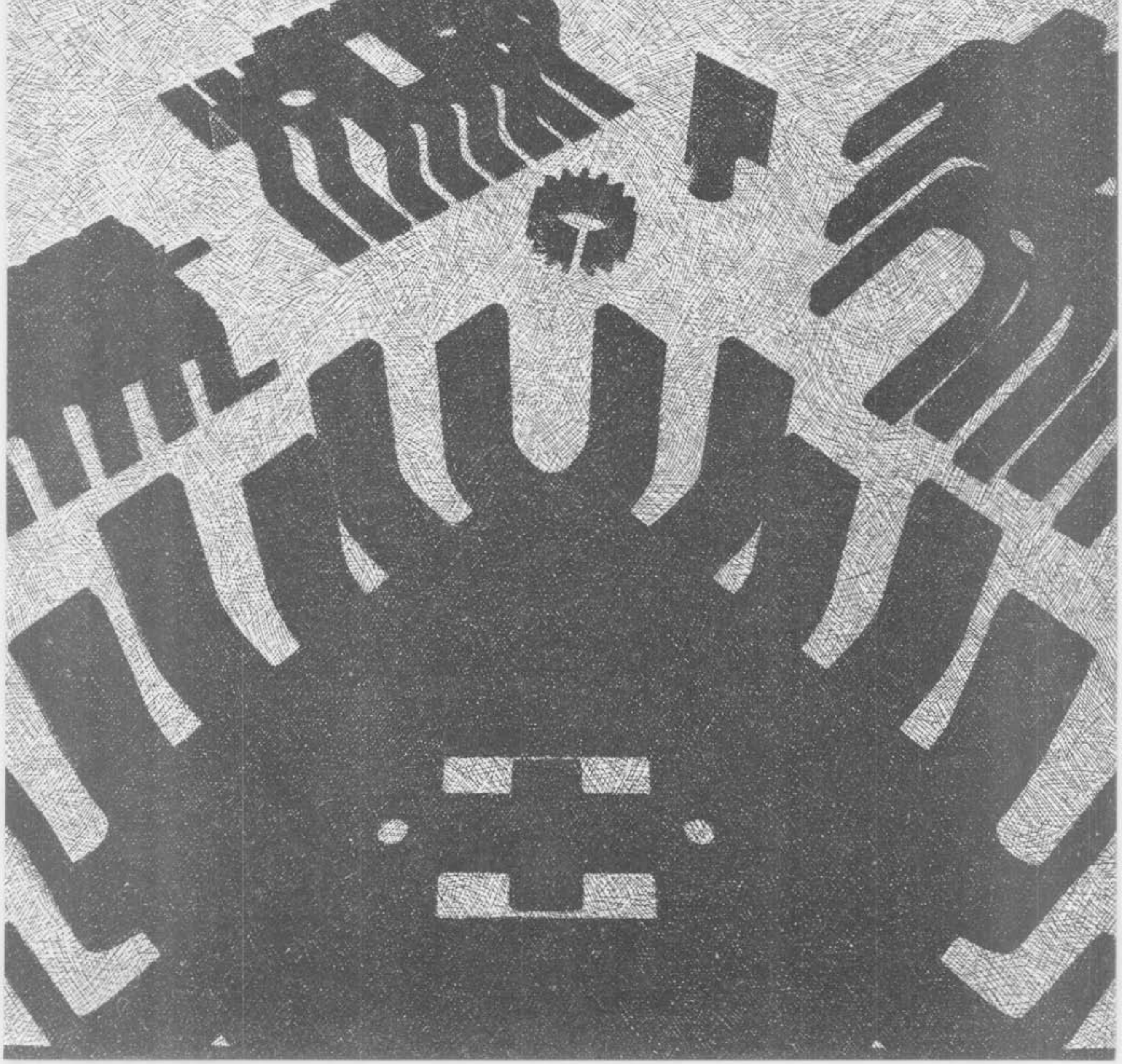



**FIGURE 4.2. Power De-Rating Curves for LM340T**

# Section 5.0
# Selection of Commercial Heat Sink



# 5.0 STANDARD HEAT SINK SELECTION PROCEDURES

## 5.1 COMPUTE TOTAL THERMAL RESISTANCE

Determine the total thermal resistance, junction to ambient $\theta_{JA(TOT)}$ necessary to maintain steady state $T_J$ below the maximum value specified in Section 3.2.

$$\theta_{JA(TOT)} = \frac{T_J - T_A}{P_D} \ °C/W \tag{5.1}$$

Under short circuit conditions, the internal thermal shutdown will limit $T_J$ to about 175 ± 15°C. Although this protects the device, prolonged operation at such temperatures can adversely effect device reliability (see Appendix 5, Reliability). If short circuit operation totaling more than 10-100 hours (For plastic package limit short circuit time to less than 1 hour) over system lifetime is expected, it is wise to use heat sinks which will limit short circuit $T_J$ to $T_{J(MAX)}$. Accordingly, check operation with $V_{OUT} = 0$. The $\theta'_{JA(TOT)}$ necessary to maintain $T_J < T_{J(MAX)}$ under short circuit conditions is

$$\theta'_{JA(TOT)} = \frac{T_{J(MAX)} - T_A}{V_{IN} I_{SC}} \ °C/W \tag{5.2}$$

where $I_{SC}$ is read from Figure 3.2. .

## 5.2 DETERMINE IF HEAT SINK IS REQUIRED

Refer to the thermal resistance, $\theta_{JC}$ and $\theta_{JA}$, columns of the data sheet summary of Section 2.

a) $\theta_{JA(TOT)} > \theta_{JC}$ must be met, otherwise a higher wattage device must be used or a boost circuit employed. (See Section 7, Applications, for boost circuits.)

b) If $\theta_{JA(TOT)} > \theta_{JA}$, a heat sink is not required.

c) If $\theta_{JC} < \theta_{JA(TOT)} < \theta_{JA}$, a heat sink is required.

## 5.3 SELECT A HEAT SINK

Choose a suitable heat sink from the selection guide, Table 5.1, or from manufacturers' specification data. The necessary conditions are that $\theta_{JA(TOT)}$ and $\theta'_{JA(TOT)}$ be less than $\theta_{JA}$, as read from Table 2.1. The total thermal resistance is that from junction to case plus that from case to ambient or sink to ambient (neglecting that from case to sink, which is small).

$$\theta_{JA(TOT)} \approx \theta_{JC} + \theta_{SA} \ °C \tag{5.3}$$

## 5.4 CHECK INPUT RIPPLE AND INPUT VARIATIONS

Insure that full-load $V_{IN(MIN)}$ does not allow $V_{IN} - V_{OUT}$ to fall below the dropout voltage of about 2 V. See individual data sheets if operation with $V_{IN} - V_{OUT} <$ 2 V is required. Insure that no-load $V_{IN(MAX)}$ does not exceed the value listed on the data sheets or in the table of Section 2.

## 5.5 EXAMPLE CALCULATION

Given: $V_{OUT} = 5\ V \pm 5\%$ $V_{IN} = 15\ V$

$I_{OUT(MAX)} = 0.7\ A$ Short circuit protected

$T_A = 60°C$ $T_J = 125°C$

Select a suitable regulator and heat sink

a) From Figure 1.2, initial selection is LM340T05, LM340K05, or LM309K.

b) From Figure 3.1, at $V_{IN} - V_{OUT} = 10\ V$, it is clear that either the LM340 or LM309 will meet the maximum current required. The LM341P is also a possibility as seen from this figure, although a marginal one on the basis of $I_{OUT(MAX)}$, and should not be considered.

c) Calculate necessary thermal resistance from Eqn 5.1

$$\theta_{JA(TOT)} = \frac{125 - 60}{10 \times 0.7} = \frac{65}{7} = 9.3°C/W$$

Since $\theta_{JA(TOT)}$ must be greater than $\theta_{JC}$ as read from Table 2.1, the LM341P is now clearly eliminated as a possibility. If not already eliminated in step (a) above, the LM309H would also drop out at this time. The selection is still limited to the LM340T, LM340K, or LM309K.

d) Since $\theta_{JA(TOT)}$ is less than $\theta_{JA}$ for any of these parts, a heat sink is required.

e) From Figure 3.2, $I_{OUT(MAX)}$ is 0.75 A or 1.4 A for the LM340 or LM309K respectively, under short circuit conditions. If extended periods of short circuit operation are expected, calculate $\theta'_{JA(TOT)}$ from Eqn 5.2.

$$\theta'_{JA(TOT)} = \frac{150 - 60}{15 \times 1.4} = \frac{90}{21} = 4.3°C/W \text{ for LM309}$$

$$\theta'_{JA(TOT)} = \frac{150 - 60}{15 \times 0.75} = \frac{90}{11.25} = 8°C/W \text{ for LM340}$$

The worst case heat sink requirement is then for short circuit conditions, and the LM340 has a lesser heat sink requirement. Further selection will depend upon hermeticity and mounting requirements. The T package is TO-220 plastic and the K package is TO-3 hermetic.

f) Choosing the LM340T, calculate heat sink thermal resistance from Eqn 5.4 where $\theta_{JC}$ is found from Table 2.1.

$$\theta_{SA} = \theta'_{JA(TOT)} - \theta_{JC} = 8 - 4 = 4°C/W \tag{5.4}$$

If we were to accept a $T_J > 150°C$ for short circuit conditions, calculations based on $\theta_{JA(TOT)}$ would yield a $\theta_{SA} = 5.3°C/W$. If an LM309K had been selected, a $\theta_{SA} = 6.3°C/W$ would be all that is required.

g) Referring to the heat sink selection guide, Table 5.1, for the TO-220 package we see that only the IERC HP3 series will come close to the 4°C/W figure. A 4°C/W heat sink is widely available for the TO-3 or K package.

h) For detailed information on heat sink design, see Section 6.

**TABLE 5.1 Heat Sink Selection Guide**

No attempt has been made to provide a complete list of all heat sink manufacturers. This list is only representative.

For TO-202 Packages

| $\theta_{SA}$ Approx[1] (°C/W) | Manufacturer & Type |
|---|---|
| 12.5 - 14.2 | Staver V4-3-192 |
| 13 | Staver V5-1 |
| 15.1 - 17.2 | Staver V4-3-128 |
| 19 | Thermalloy 6106 Series |
| 20 | Staver V6-2 |
| 25 | Thermalloy 6107 Series |
| 37 | IERC PA1-7CB with PVC-1B Clip |
| 40 - 42 | Staver F7-3 |
| 40 - 43 | Staver F7-2 |
| 42 | IERC PA2-7CB with PVC-1B Clip |
| 42 - 44 | Staver F7-1 |

For TO-220 Packages

| $\theta_{SA}$ Approx[1] (°C/W) | Manufacturer & Type |
|---|---|
| 4.2 | IERC HP3 Series |
| 5 - 6 | IERC HP1 Series |
| 6.4 | Staver V3-7-225 |
| 6.5 - 7.5 | IERC VP Series |
| 8.1 | Staver V3-5 |
| 8.8 | Staver V3-7-96 |
| 9.5 | Staver V3-3 |
| 10 | Thermalloy 6032, 6034 Series |
| 12.5 - 14.2 | Staver V4-3-192 |
| 13 | Staver V5-1 |
| 15 | Thermalloy 6030 Series |
| 15.1 - 17.2 | Staver V4-3-128 |
| 16 | Thermalloy 6106 Series |
| 18 | Thermalloy 6107 Series |
| 19 | IERC PB Series |
| 20 | Staver V6-2 |
| 25 | IERC PA Series |
| 26 | Thermalloy 6025 Series |

For TO-92 Packages

| $\theta_{SA}$ Approx[1] (°C/W) | Manufacturer & Type |
|---|---|
| 30 | Staver F2-7 |
| 46 | Staver F5-7A, F5-8-1 |
| 50 | IERC RUR Series |
| 57 | Staver F5-7D |
| 65 | IERC RU Series |
| 72 | Staver F1-7 |
| 85 | Thermalloy 2224 Series |

For TO-5 Packages

| $\theta_{SA}$ Approx[1] (°C/W) | Manufacturer & Type |
|---|---|
| 12 | Thermalloy 1101, 1103 Series |
| 12 - 16 | Wakefield 260-5 Series |
| 15 | Staver V3A-5 |
| 22 | Thermalloy 1116, 1121, 1123 Series |
| 22 | Thermalloy 1130, 1131, 1132 Series |
| 24 | Staver F5-5C |
| 26 - 30 | IERC Thermal Links |
| 27 - 83 | Wakefield 200 Series |
| 28 | Staver F5-5B |
| 30 | Thermalloy 2227 Series |
| 34 | Thermalloy 2228 Series |
| 35 | IERC Clip Mount Thermal Link |
| 39 | Thermalloy 2215 Series |
| 42 | Staver F5-5A |
| 45 - 65 | Wakefield 296 Series |
| 46 | Staver F6-5, F6-5L |
| 50 | Thermalloy 2225 Series |
| 50 - 55 | IERC Fan Tops |
| 51 | Thermalloy 2205 Series |
| 53 | Thermalloy 2211 Series |
| 55 | Thermalloy 2210 Series |
| 56 | Thermalloy 1129 Series |
| 58 | Thermalloy 2230, 2235 Series |
| 60 | Thermalloy 2226 Series |
| 68 | Staver F1-5 |
| 72 | Thermalloy 1115 Series |

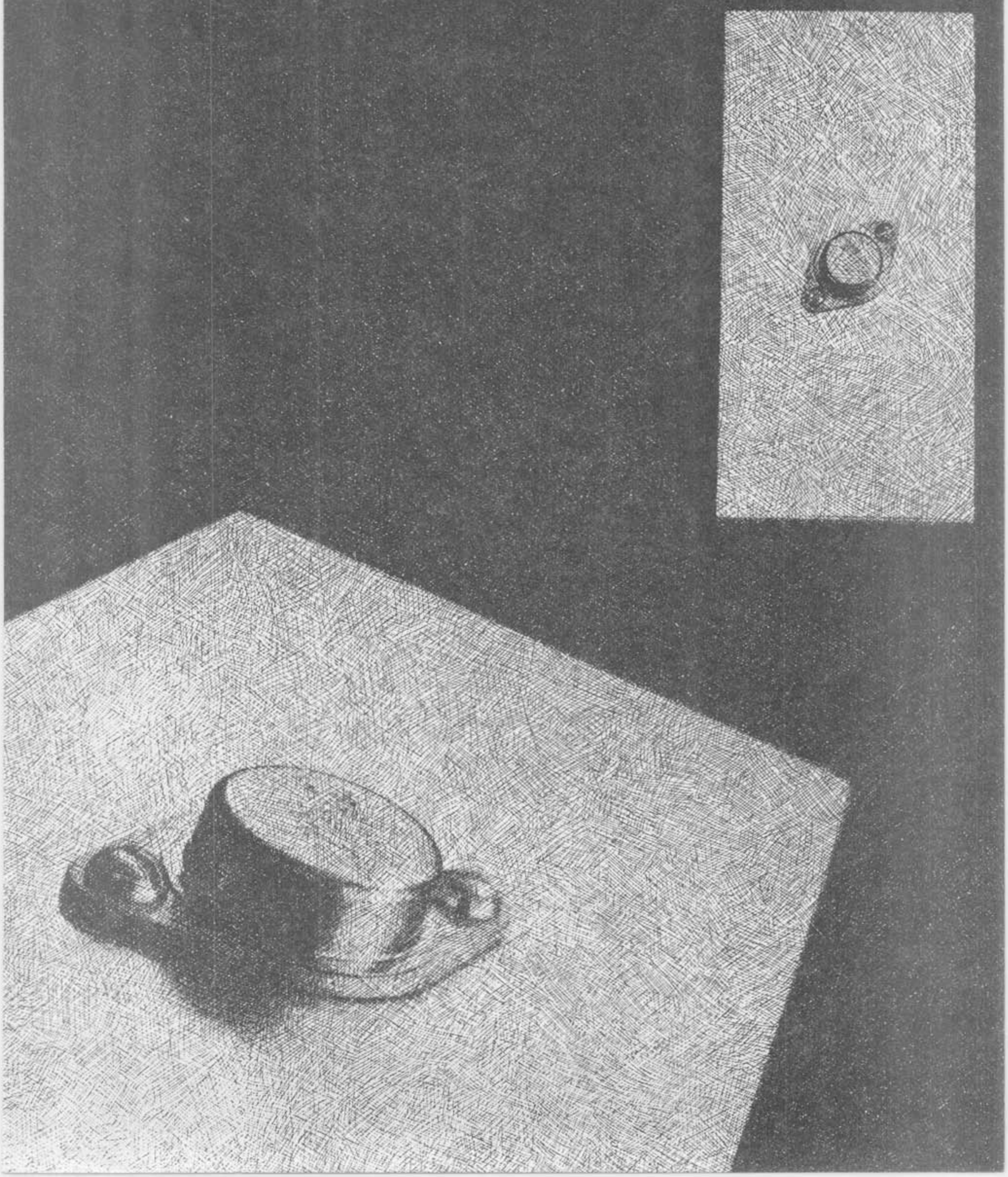
For TO-3 Packages

| $\theta_{SA}$ Approx[1] (°C/W) | Manufacturer & Type |
|---|---|
| 0.4 (9" length) | Thermalloy (Extruded) 6590 Series |
| 0.4 - 0.5 (6" length) | Thermalloy (Extruded) 6660, 6560 Series |
| 0.56 - 3.0 | Wakefield 400 Series |
| 0.6 (7.5" length) | Thermalloy (Extruded) 6470 Series |
| 0.7 - 1.2 (5 - 5.5" length) | Thermalloy (Extruded) 6423, 6443, 6441, 6450 Series |
| 1.0 - 5.4 (3" length) | Thermalloy (Extruded) 6427, 6500, 6123, 6401, 6403, 6421, 6463, 6176, 6129, 6141, 6169, 6135, 6442 Series |
| 1.9 | IERC E2 Series (Extruded) |
| 2.1 | IERC E1, E3 Series (Extruded) |
| 2.3 - 4.7 | Wakefield 600 Series |
| 4.2 | IERC HP3 Series |
| 4.5 | Staver V3-5-2 |
| 5 - 6 | IERC HP3 Series |
| 5.2 - 6.2 | Thermalloy 6103 Series |
| 5.6 | Staver V3-3-2 |
| 5.8 - 7.9 | Thermalloy 6001 Series |
| 5.9 - 10 | Wakefield 680 Series |
| 6 | Wakefield 390 Series |
| 6.4 | Staver V3-7-224 |
| 6.5 - 7.5 | IERC UP Series |
| 8 | Staver V1-5 |
| 8.1 | Staver V3-5 |
| 8.8 | Staver V3-7-96 |
| 8.8 - 14.4 | Thermalloy 6013 Series |
| 9.5 | Staver V3-3 |
| 9.5 - 10.5 | IERC LA Series |
| 9.8 - 13.9 | Wakefield 630 Series |
| 10 | Staver V1-3 |
| 13 | Thermalloy 6117 |

Staver Co, Inc: 41-51 N. Saxon Ave, Bay Shore, NY 11706
IERC: 135 W. Magnolia Blvd, Burbank, CA 91502
Thermalloy: PO Box 34829, 2021 W. Valley View Ln, Dallas TX
Wakefield Engin Ind: Wakefield MA 01880

1 All values are typical as given by mfgr. or as determined from characteristic curves supplied by mfgr.

# Section 6.0
# Custom Heat Sink Design



# 6.0 CUSTOM HEAT SINK DESIGN

## 6.1 IS A CUSTOM DESIGN NECESSARY?

The required $\theta_{SA}$ was determined in Section 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 or copper fin, to an aluminum extrusion, or to a custom heat sink. In such cases, design a simple heat sink.

## 6.2 SIMPLE RULES

a) Mount cooling fin vertically where practical for best convective heat flow.

b) Anodize, oxidize, or paint the fin surface for better radiation heat flow; see Table 6.1 for emissivity data.

c) Use 1/16" or thicker fins to provide low thermal resistance at the regulator mounting where total fin cross-section is least.

## 6.3 FIN THERMAL RESISTANCE

The heat sink-to-ambient thermal resistance of a vertically mounted symmetrical square or round fin (see Figure 6.1) in still air is:

$$\theta_{SA} = \frac{1}{2H^2\eta(h_c + h_r)} \ ^\circ C/W \qquad (6.1)$$

Where: $H$ = height of vertical plate in inches

$\eta$ = fin effectiveness factor

$h_c$ = convection heat transfer coefficient

$h_r$ = radiation heat transfer coefficient

$$h_c = 2.21 \times 10^{-3}\left(\frac{T_S - T_A}{H}\right)^{1/4} W/in^2 {}^\circ C \qquad (6.2)$$

$$h_r = 1.47 \times 10^{-10} E\left(\frac{T_S + T_A}{2} + 273\right)^3 W/in^2 {}^\circ C \qquad (6.3)$$

Where: $T_S$ = temperature of heat sink at regulator mounting, in °C

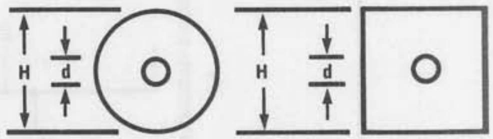
$T_A$ = ambient temperature in °C

$E$ = surface emissivity (see Table 6.1)

Fin effectiveness factor $\eta$ includes the effects of fin thickness, shape, thermal conduction, et. al. It may be determined from the nomogram of Figure 6.2.

**TABLE 6.1. 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 |




$B = \frac{H - d}{2}$ $\qquad$ $B = 0.564H - \frac{d}{2}$

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

**FIGURE 6.1. Symmetrical Fin Shapes**

The procedure for use of the nomogram of Figure 6.2 is as follows:

a) Specify fin height H as first approximation.

b) Calculate $h = h_r + h_c$ from Eqns 6.2 and 6.3.

c) Determine $\alpha$ from values of h and fin thickness x (line a).

d) Determine $\eta$ from values of B (from Figure 6.1) and $\alpha$ (line b).

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

**Horizontal mounting** - multiply $h_c$ by 0.7.

**Horizontal mounting where only one side is effective** – multiply $\eta$ 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 regulator is mounted at the bottom of a vertical fin – multiply $\eta$ by 0.7.

## 6.4 FIN DESIGN

a) Establish initial conditions $T_A$ and desired $\theta_{SA}$ as determined in Section 5.3.

b) Determine $T_S$ at contact point with the regulator by rewriting Eqn 4.1.

$$\theta_{JC} + \theta_{CS} = \frac{T_J - T_S}{P_D} \qquad (6.4)$$

$$T_S = T_J - (\theta_{JC} + \theta_{CS})(V_{IN} - V_{OUT})I_{OUT}$$
$$\approx T_J - \theta_{JC}(V_{IN} - V_{OUT})I_{OUT} \qquad (6.5)$$

c) Select fin thickness, $x > 0.0625$" and fin height, H.

d) Determine $h_c$ and $h_r$ from Eqns 6.2 and 6.3.

e) Find fin effectiveness factor $\eta$ from Figure 6.2.

f) Calculate $\theta_{SA}$ from Eqn 6.1.

g) If $\theta_{SA}$ is too large or unnecessarily small, choose a different height and repeat steps (c) through (f).

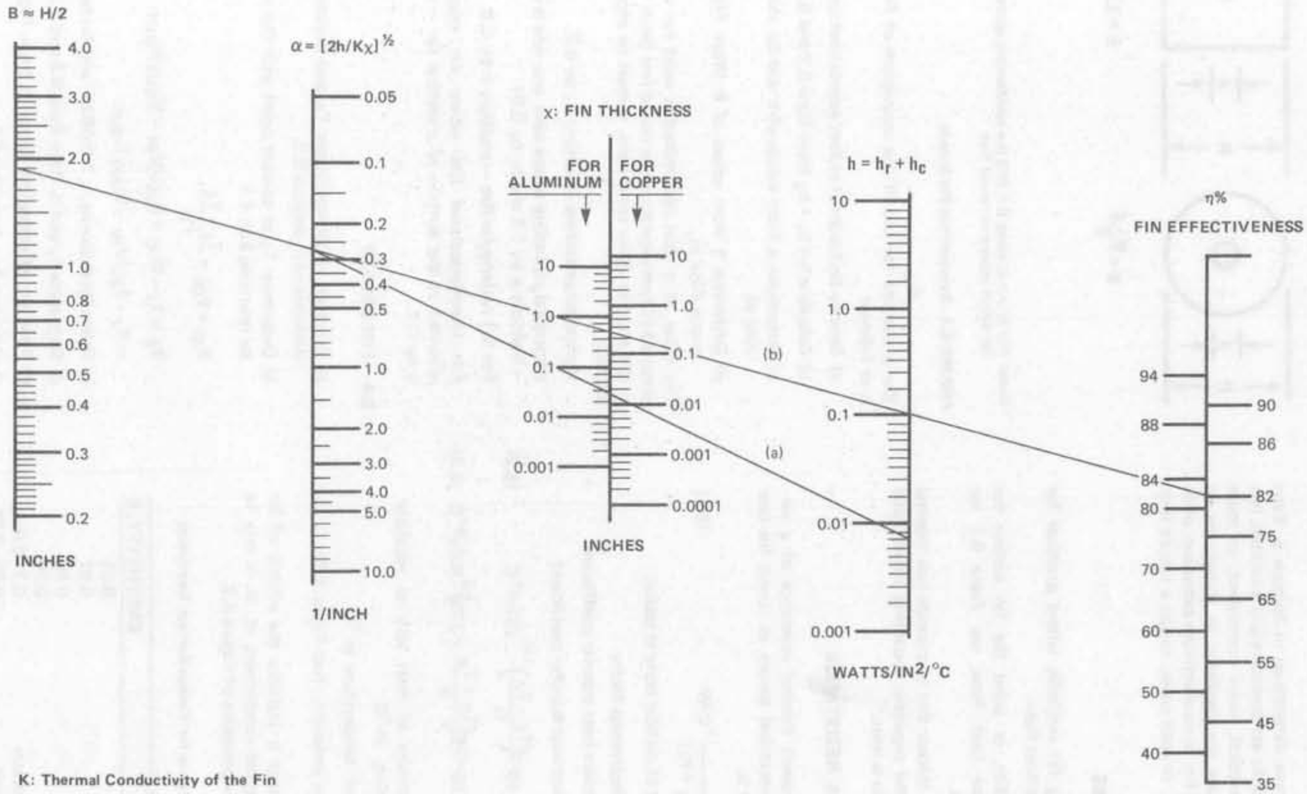



FIGURE 6.2. Fin Effectiveness Nomogram for Symmetrical, Flat, Uniformly-Thick, Vertically Mounted Fins

## 6.5 DESIGN EXAMPLE

Design a symmetrical square vertical fin of black anodized 1/16" thick aluminum to have a thermal resistance of 4°C/W. LM340T-05 operating conditions are:

a) $T_J = 125°C$ $\quad T_A = 60°C$

$V_{IN} = 15\ V$ $\quad V_{OUT} = 5\ V$

$I_{OUT} = 0.8\ A$ $\quad$ Neglect $\theta_{CS}$

b) $T_S = 125°C - 4°C/W(15\ V - 5\ V)0.8\ A = 93°C$

c) x = 0.0625" from initial conditions. E = 0.9 from Table 6.1.

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

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

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

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

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

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

e) $\eta = 0.84$ from Figure 6.2.

f) $\theta_{SA} = \frac{10^3}{2 \times 12.3 \times 0.84 \times 9.46} = 5.1°C/W$,

which is too large.

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

d') $h_c = 2.21 \times 10^{-3}\left(\frac{0.33}{4.2}\right)^{1/4} = 3.7 \times 10^{-3}$

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

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

e') $\eta = 0.75$ from Figure 6.2

f') $\theta_{SA} = \frac{10^3}{2 \times 18 \times 0.75 \times 9.3} = 3.98°C/W$,

which is satisfactory.