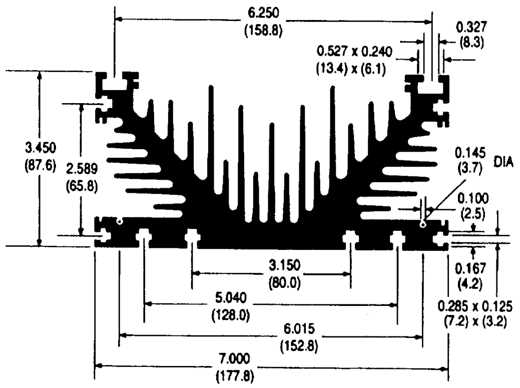
Introduction to THERMAL MANAGEMENT

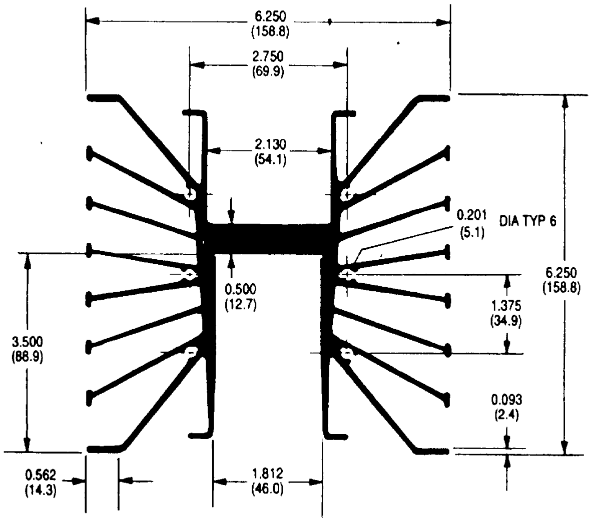
Thermal management is an important element of electronic product design. Reliable performance of these products is directly related to effectively controlling the component junction temperatures within specified limits. The maximum temperatures specified by the device manufacturers are derated by the design engineers to meet reliability criteria. Long component life may be achieved by designing the products with sufficient heat transfer components, materials, and features. Design engineers look for cost-effective ways to transfer heat from the dissipating components. The selection processes used to evaluate the thermal management components include consideration of such features as ease-of-assembly, repairability, and upgradability. A cost-effective thermal management solution must be a complete solution that takes all of these needs into account.

Many electronic components are available in a variety of packages—some of which are thermally enhanced. These packages offer improved thermal performance at the component level.

A variety of interface materials are available that span a wide range of cost, ease-of-use, and thermal performance. Typically, these materials enhance the flow of heat from the component case to the heat sink and can even provide electrical isolation when needed. With the advent of high-temperature acrylic adhesives, there are pressure-sensitive thermal tapes on the market that can eliminate fasteners in some applications. There are a variety of spring clips used to attach heat sinks to high-speed microprocessors and sockets to reduce assembly costs.



Per.	90.52	in.
WT	11.80	lb/ft
θsa	0.71	°C/W/3"



A complete thermal-management solution must include not only the component-level and interface-level thermal resistances, but also the heat sinks or other heat-transfer components used to transfer the dissipated heat to the cooling medium, typically ambient air or water.

To begin the heat-sink selection process, it is necessary to characterize the required performance. The temperature difference, sink to ambient, is the driving force that transfers the heat. The available temperature difference ("delta T") divided by the power dissipation gives a performance target in degrees – centigrade per watt (°C/W). This value, coupled with the ambient conditions (temperature and air velocity) is needed to guide the design engineer. The heat sink may be selected based on this calculated thermal-performance target while understanding the size of the component package and the space available for the heat sink.

Technical Discussion

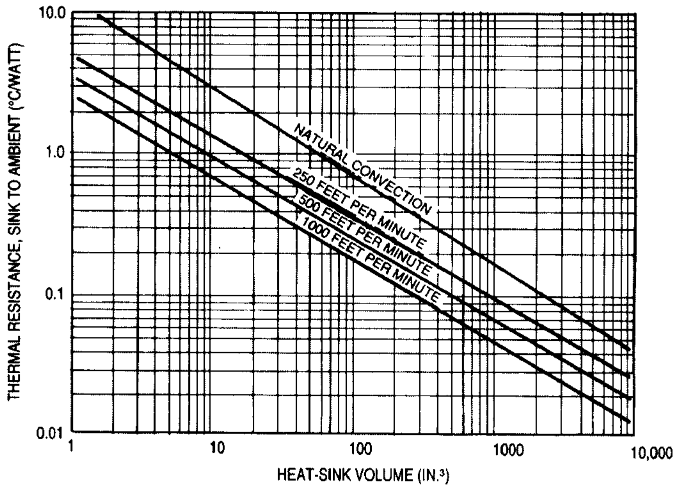
Before a heat sink is ordered, it is important to make sure that the optimum sink has been selected. In most instances, the best heat sink is not necessarily the largest or the most expensive, but rather the one that provides the best price/performance ratio and still meets the cooling requirement.

To help you make the correct selection, we have provided definitions of the most common terms used.

1. **Heat Sink**: A heat dissipator that operates as a result of the temperature difference and thermal resistances between the heat source (semiconductor) and the ambient air.
2. **Function of Heat Sinks**: To increase the surface area available for heat transfer from the semiconductor, thus lowering the temperature of the component case and junction.
3. **Thermal Resistance**: θ (theta) is a measure of the ability of a device or interface to enhance or impede the flow of heat. It is a function of temperature difference and power dissipation. The common units are degrees C per watt (°C/W).
4. **Natural Convection**: When the movement of ambient air over, around, or through a heat sink is induced by temperature differences and buoyancy effects alone.
5. **Forced Convection**: When the movement of air is induced by mechanical means (typically a fan or blower).
6. **Heat-Sink Performance**: The amount of heat that can be removed with a specified temperature difference between the heat sink and the air. It is most often characterized by thermal resistance, i.e., the lower the thermal resistance, the better the performance. The only way heat-sink performance can be improved is by increasing the physical size of the heat sink (i.e., changing surface area) or by moving more air across the sink (i.e., changing from natural convection to forced convection).

The figure below illustrates the heat-sink volume required for a range of thermal resistances, for both natural-and forced-convection applications. Typically, to reduce the thermal resistance by 50 percent, the heat-sink volume must be approximately quadrupled.

THERMAL RESISTANCE VS. HEAT SINK VOLUME



The four curves show the relationship of volume (occupied by the heat sink) to thermal resistance based on 50°C sink temperature rise above ambient.

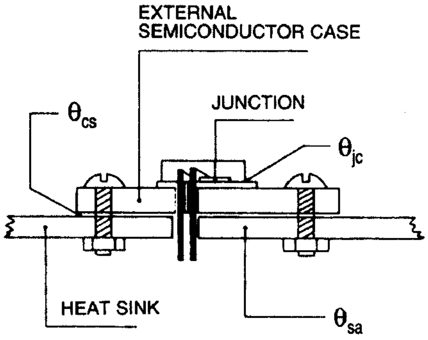
The selection of a heat sink requires knowledge of:

(1) The available volume of space to be occupied;
(2) The maximum allowable device junction temperature;
(3) The power dissipated by the device;
(4) The device configuration (package size, orientation);
(5) Ambient conditions (temperature, air velocity).

The function of a heat sink is to protect the semiconductor from the heat it produces as a by-product of its normal operation. If not removed, this heat will cause the semiconductor to exceed its safe operating temperature. In this circumstance, semiconductor performance, life, and reliability are tremendously reduced. The objective is to hold the junction temperature below the temperature allowed by the product reliability criteria.

Junction temperature is a function of the sum of the thermal resistances between the junction and the ambient air, the amount of heat being dissipated, and the ambient air temperature.

The figure below is a simplified drawing of a semiconductor mounted on a heat sink. Three thermal resistances are readily identified:



The total resistance, θ_{tot}, is the sum of these individual resistances:

$$\theta_{tot} = \theta_{jc} + \theta_{cs} + \theta_{sa} \qquad \text{(Equation 1)}$$

1. **Thermal resistance from junction to case.** This resistance is designated θ_{jc} and is expressed in °C/watt. This resistance is a function of design and manufacturing methods and is specified by the manufacturer for each semiconductor device.
2. **Thermal resistance from case to heat sink.** This interface resistance is designated θ_{cs} and is expressed in °C/watt. It is a variable which can be minimized by the use of Wakefield Engineering DeltaPads™ or the application of a thermal grease or paste such as the Wakefield Series 120 or 126 Thermal Joint Compounds. These compounds and pads reduce the high thermal impedance of the air gap between the case and the sink.
3. **Thermal resistance from sink to ambient.** This resistance is designated θ_{sa} and is also expressed in °C/watt. This is the resistance used in the selection of the heat sink. The smaller this value is, the more power the device can dissipate without exceeding its junction-temperature limit. The thermal resistance from sink to ambient (θ_{sa}) is a function of the convection heat-transfer

Technical Discussion (Cont.)

coefficient (h_c) and the surface area (A) of the heat sink as shown in the formula:

$$\theta_{sa} = \frac{1}{h_c A} \qquad \text{(Equation 2)}$$

The heat-transfer coefficient, h_c, is a complex function and can be derived from a variety of empirical correlations for both natural and forced convection. To aid the user, we have provided graphs and examples based on theory and experience that should give reasonable accuracy in the selection process.

As this formula indicates, θ_{sa} is the reciprocal of the product of the heat transfer coefficient and the sink surface area. So, the value of θ_{sa} can be minimized by maximizing this product of h_c times A. Increasing the surface area will not always increase the product of h_c times A. In fact, if the added surface area (more fins) chokes the air flow, the h_c value can be decreased so much that the product of h_c times A is actually reduced, increasing the θ_{sa} value rather than decreasing it. Please consult our Applications Engineering Department for assistance in this area

With a semiconductor mounted on a heat sink, the relationship between junction temperature rise above ambient temperature and power dissipation is given by

$$Q = \frac{T_j - T_a}{\theta_{jc} + \theta_{cs} + \theta_{sa}} \qquad \text{(Equation 3)}$$

where

Q = power dissipated, watts

T_j = junction temperature, °C

T_a = ambient air temperature, °C

θ_{jc} = thermal resistance from junction to semiconductor case, °C/watt

θ_{cs} = thermal resistance from case to heat sink, °C/watt

θ_{sa} = thermal resistance from surface of heat sink to ambient air, °C/watt

In most applications, values for all these parameters are known or can be found except that for the maximum thermal resistance from heat sink surface to air, θ_{sa}. The value of this parameter then becomes the basis for sink selection.

Equation 3 is the basic equation and is correct for either natural or forced convection cooling. Data for heat sink selection with forced convection are generally presented in terms of θ_{sa}, but for natural convection, data are presented in terms of ΔT_{sa} (temperature difference between sink and air). This results in the following simplified form of Equation 3:

$$\Delta T_{sa} = (T_j - T_a) - Q\ (\theta_{jc} + \theta_{cs}) \qquad \text{(Equation 4)}$$

It eliminates the requirement of multiplying θ_{sa} by Q to obtain the maximum allowable ΔT_{sa} and thus gives that parameter for direct comparison with data as presented on most natural convection graphs.

For example, assume a semiconductor with a TO-3 case must be operated so that its junction temperature will not exceed 125°C when it is dissipating 10 watts to ambient air at a temperature of 50°C. The value of θ_{jc} for this device established by the manufacturer is 1.5°C/watt and θ_{cs} is estimated to be 0.09°C/watt because Wakefield Series 120 Thermal Joint Compound is being used.

The thermal schematic of this example would look like this:

Max. semiconductor junction temp. (T_j) 125°C

θ_{jc} = 1.5°C/W

Case Temp. (T_c)

θ_{cs} = 0.09°C/W

Sink Temp. (T_s)

θ_{sa} = ?

Ambient air temp. (T_a) 50°C

Solving Equation 3 above for the unknown value of θ_{sa} (thermal resistance from sink to air) produces the following equation:

$$\theta_{sa} = \frac{T_j - T_a}{Q} - (\theta_{jc} + \theta_{cs}) \qquad \text{(Equation 5)}$$

Inserting known values into Equation 5 as follows:

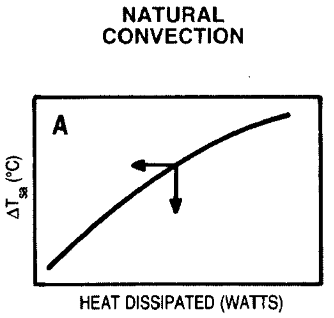
$$\theta_{sa} = \frac{125 - 50}{10} \quad (1.5 + 0.09)$$

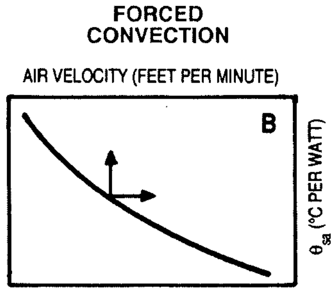
$$\theta_{sa} = 5.9°\text{C/watt}$$

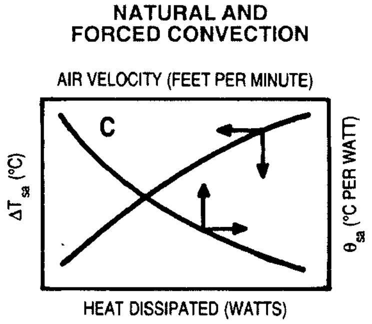
This is the largest value of θ_{sa} that can be used. Heat sinks providing smaller values of θ_{sa} are also acceptable since the resulting junction temperatures will be less than the 125°C specified. With this value of θ_{sa} we could then proceed to the data presented for various heat sinks and locate one which will provide this performance.

The product data presented herein shows operating performance for both natural and forced convection.

Natural convection data is presented as Heat Sink Temperature Rise versus Heat Dissipated (ΔT_{sa} vs. Q) as shown (Figure A). Forced convection data is presented as θ_{sa} versus air velocity (Figure B). Figure C is a composite of Figures A and B.







Selecting Extrusions for Natural Convection

To make use of the data presented and to offer a suggested selection method for extrusion lengths other than 3 inches, Wakefield Engineering has developed the size selector graph shown below. Once the preferred extrusion is selected, this graph will assist in establishing the approximate length necessary to obtain a desired thermal resistance. It is assumed that device quantity and location add no unusual heat distribution effects.

Example of Graph Use

Suppose it is desired to use extrusion number 1881 and have a thermal resistance of 2.8°C/watt. Looking into the tabular data section, we find the thermal resistance is 3.9°C/watt for a 3-inch length.

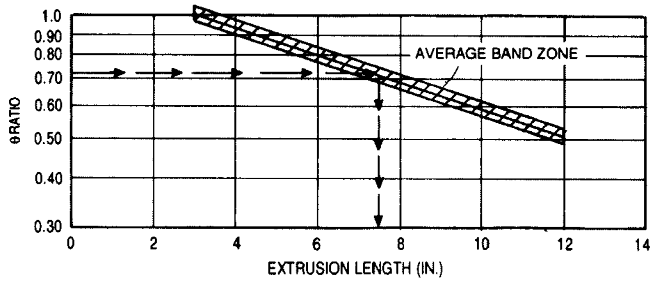
$$\theta \text{ ratio is defined as } \frac{\theta \text{ desired}}{\theta \text{ for a 3-inch length}}$$

$$\text{Then } \theta \text{ ratio for our example is } \frac{2.8}{3.9} = 0.72$$

Reading horizontally across at a θ ratio of 0.72, we find the approximate center of the shaded zone and read vertically down to determine that the length required is 7.5 inches. Any length greater than this would also be acceptable at the user's option.

It is important to note that the selector values are based on design assumptions where the extrusion length is mounted in the vertical position only and includes the effects of black anodizing.

NATURAL CONVECTION SIZE SELECTOR

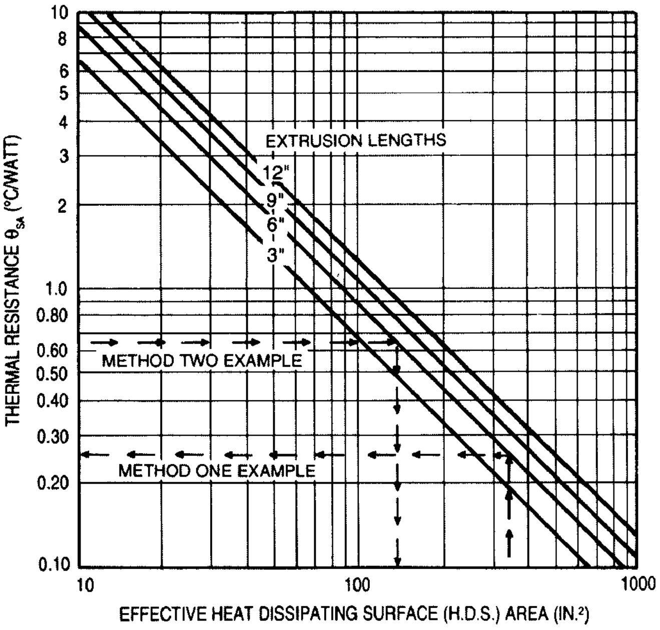


Selecting Extrusions for Forced Convection

Up to this point, almost all discussions in selecting heat sinks have been predicated on using natural convection heat transfer where the only way to reduce the sink to air thermal resistance θ_{sa} was to increase the surface area of the sink. But, as briefly stated in previous discussions, similar reduction in θ_{sa} can be obtained if the thermal coupling between the heat sink and the ambient air is improved, i.e., increase in the heat transfer coefficient, h_c. This can be achieved by forced convection methods using blowers, fans, and ducts.

The forced-convection performance of Wakefield heat sinks can be estimated from the following graph developed for that purpose. In its preparation, we have combined theory and experience and factored in some basic assumptions that should yield reasonable and useful information. More importantly, we have tried to address the many questions concerning the relationship of thermal performance and extrusion length. The engineering data supporting the graph are based on air movements in the laminar region (frontal velocities of approximately 400 to 800 FPM) and should be understood to be useful approximations of predicted thermal performance. As in natural convection, it is again assumed that device quantity and location add no unusual heat distribution effects.

FORCED CONVECTION SIZE SELECTOR



In our efforts to generalize, it is difficult to provide a specific rule that satisfies all conditions, but when forced convection is considered, it is important to make an assessment of the temperature change of the air. When making these calculations, we must check to see if our operating set of conditions keeps the air from rising above effective functional limits. As air moves through the extrusion, it accepts the heat produced by the input wattage, causing a rise in temperature along its length. It is imperative that the outlet temperature of the air never exceed the desired maximum surface temperature of the heat sink and in fact should remain as far below this temperature as is practical.

The temperature rise of the ambient air can be calculated by:

$$\Delta T = \frac{1.76Q}{V} \qquad \text{(Equation 6)}$$

where:

ΔT = increase in ambient air temperature, °C
Q = heat dissipation, watts
V = volumetric flow rate, cfm
1.76 constant is based on a 25°C ambient air temperature

For ambient temperatures greater than that specified above, multiply the calculated ΔT by the following temperature factors.

Air Temperature °C	**Temperature Multiplier Factor**
30	1.02
40	1.06
50	1.09
60	1.12

Selecting Extrusions for Forced Convection (Cont.)

Example of Graph Use

a) Method One: Predicting performance of an existing shape and length.

Let us assume that we are considering using Wakefield Extrusion Number 4640, 6 inches long, and would like to determine the expected thermal performance. Looking into the tabular data, we find that the heat dissipating surface (HDS) is 57.8 in.^{2}/in. The total HDS area is then 57.8 in.^{2}/in. x 6 in. = 347 in.^{2}. Using the graph (Forced Convection Size Selector) on page 6, locate the HDS area line at 347 and go vertically up until you intersect the 6-inch length line; then go horizontally to the left and read a thermal resistance of 0.26°C/watt.

b) Method Two: With a design goal of 0.65°C/watt, determine the required extrusion length.

Because of the additional length variables using this method, it is suggested an averaging technique be used based on the four lengths presented.

Let us assume that we are again using the preferred extrusion, Wakefield Number 4640. Starting at the left side of the graph, locate the thermal resistance of 0.65°C/watt. Move horizontally to the right until you intersect each of the length lines and reading vertically down record the HDS value for each of the lengths. Determine the arithmetical average by dividing the sum of these readings by four. For our example, the average HDS is calculated as follows:

at 3 in. length, HDS = 103
at 6 in. length, HDS = 137
at 9 in. length, HDS = 165
at 12 in. length, HDS = 195

$$\text{Average HDS} = \frac{103 + 137 + 165 + 195}{4} = 150$$

Remembering from the example above in Method One that the HDS area is 57.8 in.^{2}/in., we can find the required length by simple division.

$$\text{Required Length} = \frac{\text{required average surface area}}{\text{actual surface area/inch}}$$

$$= \frac{150}{57.8} = 2.6 \text{ inches}$$

Any length greater than this would also be acceptable at the discretion of the user. For intermediate lengths, it would be reasonable to extrapolate the required values. For purposes of this forced convection exercise, it should be noted that the effects of black anodizing do not contribute to performance and can generally be ignored.

In Method One, we determined that using a Wakefield Extrusion No. 4640, 6 inches long, yielded a thermal resistance, θ_{sa}, of 0.26°C/watt. Now let us apply some operating conditions to check for functional effectiveness.

Assume:

200 watts input distributed uniformly
40°C maximum ambient temperature
110°C maximum heat sink temperature
55 cfm assumed airflow

Calculate air temperature rise:

$$\Delta T = \frac{1.76Q}{V} = \frac{1.76\,(200)}{55} = 6.4°C$$

Correcting this to operating conditions by using the multiplying factor:

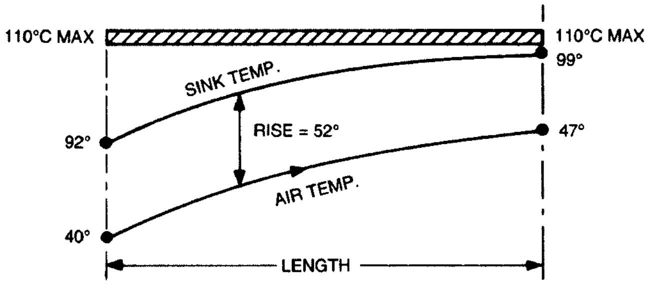
ΔT corrected = 6.4 x 1.08 (assumed) = 6.9°C (use 7.0°C)

Calculated heat sink temperature rise then is:

ΔT sink = θ_{sa} x input watts = 0.26 (200) = 52°C

To visualize this more clearly, it is sometimes useful to show these temperature profiles graphically as follows:

HEAT SINK REQUIREMENTS



From the conditions set forth and the operating assumptions, this application suggests that the performance will stay within acceptable limits.

Improving Thermal Performance

The objective is to keep the junction temperature below the allowable limits. If overall performance is defined as the amount of heat that can be removed with a specified temperature difference between the semiconductor junction and the ambient fluid (usually air), Equation 3 is rearranged as follows:

$$\theta_{ja} = \theta_{jc} + \theta_{cs} + \theta_{sa} = \frac{T_j - T_a}{Q} \qquad \text{(Equation 7)}$$

Now, overall performance can be stated simply as thermal resistance (θ_{ja}), and it is equal to the sum of the thermal resistances previously mentioned. The lower the thermal resistance, the better the performance.

To optimize this overall performance, one must achieve the required θ_{ja} at minimal cost. This can be accomplished by re-examination of each of the three thermal resistances involved.

1. **θ_{jc} is controlled by the manufacturer of each semiconductor and is therefore a fixed resistance value.**

2. **θ_{cs}**
   Again, the objective is to minimize this interface resistance, thus reducing the size of the required heat sink to achieve the desired overall performance (θ_{ja}). However, the value of θ_{cs} is not simply selected from a manufacturer's data sheet like θ_{jc}; it may have to be calculated for your particular application.

Improving Thermal Performance (Cont.)

In order to calculate θ_{cs}, it is necessary to review how heat is transferred across an interface. Of the four possible heat transfer paths, the first two dominate. First, there is conduction between mating solid surfaces. Second, there is conduction through the material that fills the voids caused by surface irregularities. Third, there is radiation across the voids, provided they contain a transparent medium such as air (for the temperatures involved in semiconductor electronics, radiation heat transfer across the interface is minimal). Finally, convection does not occur because the small dimensions of the voids preclude adequate fluid motion.

Conduction heat transfer is a function of a material thermal conductivity (K), the cross-sectional area (A_1) that the heat is flowing through, and the length or thickness (l_1) of the thermal path that the heat travels. Now, from a strictly theoretical viewpoint, the way to improve (lower) θ_{cs} is to raise the thermal conductivity of the interface material or increase the cross-sectional area or reduce the thermal path length. This is readily seen below:

$$\theta_{cs} = \frac{l_1}{KA_1} \qquad \text{(Equation 8)}$$

This equation can be converted into terms that are easier to utilize by considering the thermal resistivity of each material:

$$\theta_{cs} = \rho t/A \qquad \text{(Equation 9)}$$

where

ρ = thermal resistivity (°C)(in.)/watt
t = average layer thickness, inches
A = contact area, square inches

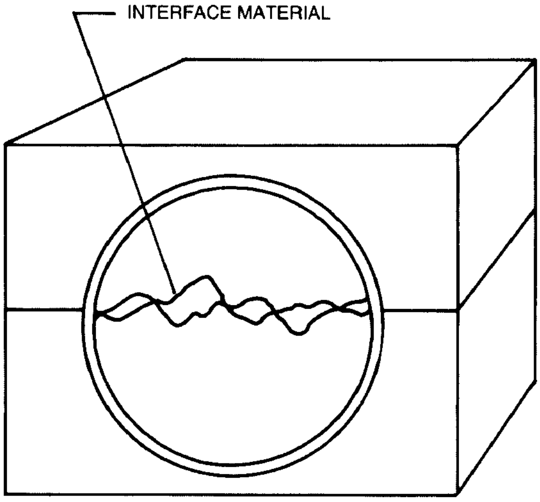
Table 1 lists the ρ value for various materials. As the table shows, still air has the highest (worst) ρ value.

Table 1. Typical Values for ρ, Thermal Resistivity.

Materials	(° C)(in.)/(watt)
Still air	1200
Silicone grease	204
Mylar film	236
Mica	66
DeltaPad 175-6	91
DeltaPad 173-9	56
Series 120 Joint Compound	56
Series 121 Joint Compound	56
Type 126 Joint Compound	57
Types 152 & D and 153 & D	54
Type 151 DeltaCoate	48
DeltaPad 173-7	47
Types 152 & A and 153 & A	47
Types 152 & B and 153 & B	42
Types 152 & C and 153 & C	42
Type 156K	79
DeltaPad 174-9	28
PSA Laminates	35-90
Filled Silicone Rubber	81
Anodized Coating	5.6
Alumina	1.15
Steel, Carbon	0.84
Boron Nitride	0.60
Beryllium Oxide	0.32
Aluminum Type 1100	0.19
Copper, CDA110	0.10

***NOTE:** For other materials, divide 273 by the (Btu)(in.)/(hr)(ft2)(°F) value of the material.

When a magnified view of the interface is examined, it becomes evident that a dry mount of an electronic device to its heat sink has a high θ_{cs} because of the large contact area where still air, with its high ρ, is the interface material. Even though the two mating parts (i.e., transistor and heat sink) may be made of low ρ value material such as copper, their inherent surface roughness and flatness variations actually result in a small solid-to-solid contact area. Even polished surfaces will have enough microscopic air pockets to suggest that interface materials should be used to minimize θ_{cs}. Proper treatment of this interface resistance is critical for good thermal performance in applications that have high heat fluxes resulting from high heat-transfer rates needed across small interface areas.



Almost any method of mounting a semiconductor device to its heat sink is better than just a dry mount. The optimum would be to use only a thermal joint compound (Series 120 or 126) with no electrical isolation. If electrical isolation between the device and heat sink is required, then beryllium oxide wafers (Series 177) and thermal joint compound or DeltaPad™ Thermally Conductive Insulators (Series 173 and 174) should be used. It would be desirable, in forced convection applications, if electrical isolation between the device and ground is necessary, that the heat sink be isolated from its mounting surface (through use of Series 100 insulators) rather than between the device and the heat sink. This enhancement technique will result in a significant reduction of the overall thermal resistance (θ_{ja}) while still providing electrical isolation from the chassis.

Typical Interface Resistances for Various Mounting Methods with a TO-3 (interface area = 1 in.^{2}):

Example 1. θ_{cs} using Equation 9 and Table 1:

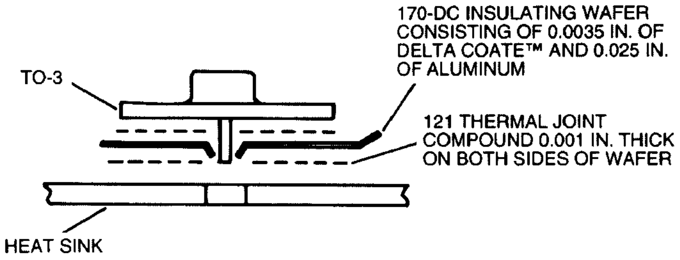
Thermal Joint Compound only (0.001 thick)	θ = 0.056°C/W
Mica (0.005) and Joint Compound (0.002)	θ = 0.44°C/W
Series 177 Beryllium Oxide Wafers (0.062) and Joint Compound (0.002)	θ = 0.13°C/W
DeltaPad™ 173-9 (0.009)	θ = 0.50°C/W
Dry Mounting (0.001 assumed)	θ = 1.2°C/W

The calculation of θ_{cs} is relatively simple, provided that for each interface layer, the material, its thickness, and the cross-sectional area through which the heat is flowing are known.

Improving Thermal Performance (Cont.)

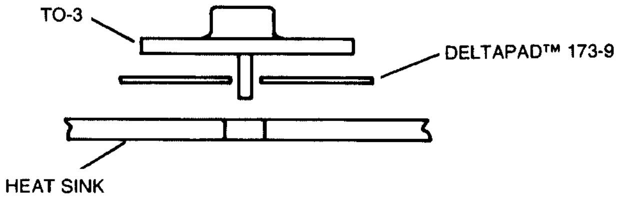
Example 2. Assume a semiconductor device in a TO-3 case style is to be mounted on a heat sink with a part number 170-DC Insulating Wafer as shown in the following figure. The actual layers in that interface would be:

0.001 in.	Type 120 Thermal Joint Compound	$\theta = 0.056$
0.0035 in.	DeltaCoate™ 151	$\theta = 0.168$
0.025 in.	Aluminum	$\theta = 0.005$
0.001 in.	Type 120 Thermal Joint Compound	$\theta = 0.056$
	Total	$\theta = 0.285$°C/Watt



Example 3. Assume a semiconductor device in a TO-3 style case is to be mounted on a heat sink with a DeltaPad™ Thermally Conductive Insulator No. 173-9. The actual layer in that interface would be:

0.009 in.	DeltaPad™ 173-9	$\theta = 0.50$°C/W



3. θ_{sa}

Now that the prior two thermal resistances (θ_{jc} and θ_{cs}) have been determined, the required heat sink thermal resistance is calculated, because the overall performance (θ_{ja}) was initially specified. It is assumed that θ_{jc} and θ_{cs} have been optimized, so now the question is how to satisfy θ_{sa}.

θ_{sa} is determined by the following modes of heat transfer: conduction through the heat sink material to the dissipating surface area; convection (natural or forced); and radiation from the heat sink surface area. Therefore, it can be simplified and expressed as follows:

$$\theta_{sa} = \frac{\rho l_1}{A_1} + \frac{1}{h_c A_2 + h_r A_3} \qquad \text{(Equation 10)}$$

The first group of terms represent the conduction component of θ_{sa} where A_1 is the average cross-sectional area available for heat flow by conduction, l_1 is the average path length that the heat must take, and ρ is the thermal resistivity of the heat sink material. The second group of terms in the equation represent the convection component of the sink's thermal resistance where h_c is the convection heat transfer coefficient and A_2 is the heat sink area in contact with the moving ambient fluid. The third group of terms represent the radiation component where h_r is a simplified expression and can be called the radiational heat transfer coefficient. Finally, A_3 represents the effective area available for radiation heat transfer. In most heat-sink designs, A_3 is significantly less than A_2.

The reason for breaking down θ_{sa} into the three components described above is that it allows examination of each part with the objective of improving performance (lowering θ_{sa}). The first group of terms is basically the same as θ_{cs} except that the actual heat sink material, rather than the interface material, is being considered. Obviously, this group's thermal resistance can never be reduced to zero because it represents the material necessary for the flow of heat from the interface to the actual dissipating surfaces. But, the objective would still be to minimize l_1, and maximize A_1 where possible.

In the second group of terms in Equation 10, the objective is to maximize A_2. The value of h_c is not easily changed because it is predominately a function of temperature (heat sink surface and ambient fluid) and fluid velocity. In natural convection, the fluid velocity is essentially controlled by buoyancy effects within the fluid. Improving h_c usually requires an increase in the temperature differential between the sink surface and the ambient fluid which is directly opposite our goal of lowering θ_{sa}!

In forced convection, h_c is significantly larger (3 to 4 times) than the value in natural convection. But again, unless the fan size is increased, little improvement in fluid velocity is possible, and thus little change in h_c. So, once an operating temperature differential (ΔT_{sa}) or a fan is specified, it is usually easier to increase A_2 rather than h_c.

For the third group in Equation 10, h_r is a function of the emissivity of the heat sink surface (black body has an ε of 1.00) and temperature differential. Again, as in the second group, improving h_r by increasing ΔT is not the objective. However, a clean, smooth aluminum surface has an ε value of about 0.10, while a black anodized or painted surface will be about 0.90; thus, it is obvious that a heat sink's performance in natural convection can be significantly improved (10-15%) by just blackening the surface. In forced convection, the amount of heat being dissipated by radiation is so small (3%) that the added cost of blackening is not justified.

It should be noted again that A_3 is not the same as A_2. In this case, A_3 represents the effective radiational surface area and with normal extruded heat sink designs (i.e., fins that are 4 times higher than the spacing between them) it is only about 20% of A_2. Generally, an increase in surface area A_2 will result in the same proportional improvement of A_3.

Integrated Circuit Heat Sinks

Traditional heat sinks are often thought of as extruded aluminum unidirectional fin heat sinks. For IC applications, the standard design today is the omnidirectional pin fin design; Wakefield Engineering has offered these as standard designs since 1984. As microprocessor speeds have risen and gate array functionality has increased, most of the series shown in this catalog have been designed within the last three years. Radial fin heat sinks, typically found in large computer systems with high airflow rates, are generally not found in notebook and desktop PC designs. A general categorization of typical heat sink application by system parameter can be shown based on available enclosure airflow:

	Heat Sink Type				
Typical Application by Airflow Range	**Radial Fin**	**Unidirectional Fin**	**Omnidirectional Pin Fin**	**Convoluted Fin**	**Fan Sink**
Natural Convection (Any system) 0 LFM		+	+	△	+
Notebook/Laptop 0 LFM		+	+	△	□
Card Level 0-50 LFM	□	+	+	△	□
Desktop 0-200 LFM	□	+	+	□	+
Servers 200-400 LFM	□	+	+	+	+
Large Systems 300-700 LFM	+	□	+	+	△

Key: + Most suitable for typical applications □ May be used for typical applications
△ Unsuitable for typical applications

Note: Airflow ranges are identified by general category of computer system. These are general statements meant to serve as a guide. Convoluted fin heat sink assemblies generally require ducted airflow.

Penguin™ Coolers, integrated circuit heat dissipation components, are designed and manufactured by Wakefield Engineering and typically provide thermal resistance values in the following general ranges (θ_{sa}):

Heat Dissipation Component Type	Typical θ_{sa} Values
Pin Fin, Unidirectional Fin, Radial Fin Heat Sinks	0.80°C/W to 12.00°C/W
Convoluted Fin Heat Sink or Assemblies	0.05°C/W to 0.50°C/W
Liquid Cold Plates	0.01°C/W to 0.10°C/W
Fan sinks	0.50°C/W to 1.30°C/W

Two Penguin™ Coolers Engineering Evaluation Kits (P/N 200, P/N 300) are available for design engineers selecting from the many Wakefield Engineering standard designs available.

Heat Sink Attachment Methods and Options

Heat sink attachment methods are becoming increasingly important, providing clamping for heat sinks used with thermal interface materials; loading forces for secure heat sink retention in shock and vibration testing; and reduction of assembly time in manufacturing. Heat sinks for most ceramic pin grid arrays may be attached using several methods:

- Adhesive attachment to the IC package;
- Clip attachment to certain ceramic PGAs;
- Clip attachment to certain PGA sockets;
- Other mechanical attachment mechanisms.

The choice of attachment method is most frequently made based on evaluation of annual heat sink usage volumes and the requirements of an OEM's manufacturing operations. Clip designs such as the Wakefield Engineering 639 Series SnapClip™ assemblies attach manually with no tools to IntelDX4™ and other 486-based microprocessors packaged in 17 x 17 PGAs. Other designs, such as the Wakefield SpiderClip™ types, attach to 17 x 17, 18 x 18, and 19 x 19 PGAs with Wakefield-designed assembly tools; these types provide attachment on all four sides of the PGA and are also ideal for use with microprocessors used without sockets. Wakefield SocketClip™ assemblies are used with certain socket manufacturers' PGA LIF and ZIF sockets for secure retention of the heat sink and processor, including all versions of the Intel Pentium™ Processor family.

Other mechanical attachment mechanisms include nut and lockwasher application to retain heat sinks adapted for ceramic PGAs with single- and dual-threaded stud features, such as the Digital Alpha AXP processors and Hewlett-Packard PA RISC processors. A less common example is the retention of an external heat sink with a custom clip designed to attach across the heat sink and IC to through-holes located in the printed circuit card for this purpose (used for high leadcount surface-mount package types such as CQFPs and BGAs).

Liquid Adhesives and Pressure-Sensitive Adhesives

Wakefield Engineering offers three types of liquid adhesives and two pressure-sensitive adhesives (PSAs—supplied preapplied to the base of Wakefield heat sinks) in pre-form format for general usage with Penguin™ Coolers:

Available Standard Liquid Adhesives and Pressure-Sensitive Adhesives

Wakefield Adhesive Designation	Adhesive Type and Description
DeltaBond™ 152	Thermally conductive two-part epoxy, requires elevated temperature curing.
DeltaBond™ 154	Highly thermally conductive two-part epoxy; requires elevated temperature curing.
DeltaBond™ 156	Modified acrylic two-part adhesive; cures at room temperature; ideal for Deltem™ composite heat sinks.
P/N Suffix "T1"	Chomerics Inc. ThermAttach™ T-405 pressure-sensitive adhesive (PSA).
P/N Suffix "T2"	Adhesives Research Inc. ARClad™ 8223 pressure-sensitive adhesive (PSA).
P/N Suffix "T3"	Chomerics Inc. ThermAttach™ T-412 pressure-sensitive adhesive (PSA).

See Accessories Section of the Wakefield Engineering Catalog for additional information regarding the DeltaBond™ 152, 154, and 156 adhesive types and available hardeners.

Comparative Data, Thermally Conductive Pressure-Sensitive Adhesives

PSA Product	Thermal Performance		Cohesive Strength
(P/N Suffix)	Thermal Conductivity (W/m°K)	Thermal Impedance (°C in.^{2}/W)	Lap Shear (lbs/in.^{2})
T1	0.50	0.50	135
T2	0.62	0.25	120
T3	1.40	0.25	70

Additional information is available from Wakefield Engineering's Applications Engineering Department.

Application of PSA Adhesives

These pressure-sensitive adhesives are electrically conductive and are designated by part number suffixes "T1," "T2," and "T3," supplied preassembled to the base of the appropriate heat sink. To attach the heat sink to the IC package, a release liner is removed from the PSA and the heat sink is placed with minimal pressure applied (10 PSI or less). Proper cleaning of the attachment surface with isopropyl alcohol is recommended. Use of a hot air gun for a 10-second preheating of the PSA pre-form will aid in wetting of the PSA prior to attachment. Electrically conductive "T1," "T2," and "T3" PSAs are manufactured from adhesives laminated to an 0.002 in.-thick aluminum foil carrier. Other PSA pre-forms are also available upon request as nonstandard items, including electrically nonconductive PSAs.