International
IOR Rectifier

# Application Note AN-1057

## Heatsink Characteristics

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In many electronic applications, temperature becomes an important factor when designing a system. Switching and conduction losses can heat up the silicon of the device above its maximum Junction Temperature (Tjmax) and cause performance failure, breakdown and worst case, fire. Therefore the temperature of the device must be calculated not to exceed the Tjmax. To design a good Thermal Management solution, the Tj should always be kept at the lowest operating temperature.

# Heatsink Characteristics

*By Llew Edmunds, International Rectifier. References to Aavid Thermalloy,*

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## Introduction

In many electronic applications, temperature becomes an important factor when designing a system. Switching and conduction losses can heat up the silicon of the device above it's maximum Junction Temperature ($Tj_{max}$) and cause performance failure, breakdown and worst case, fire. Therefore the temperature of the device must be calculated not to exceed the $Tj_{max}$. To design a good Thermal Management solution, the Tj should always be kept at the lowest operating temperature.

## Maximization of Thermal Management

Thermal management should be determined at the board layout design stage, not later. It is feasible and less costly to determine the thermal load at your design process of the pcb board. The ability to design in optimal solutions, more flexibility, more choices, and also to save possible device failures after the design has been finalized. Most of the problems occurring at the end of the design cycle are due to thermal management considerations.

## Heat Transfer Basics

Heat transfer occurs when two surfaces have different temperatures, thus causing heat energy to transfer from the hotter surface to the colder surface. For example, voltage is the driving force that causes current to flow. By analogy, temperature is the force that causes heat to flow. If the temperature difference is increased, the amount of heat flow will be increased:

***Heat transfer*** $\alpha$ ***temperature difference***

**Terms and Definitions**

| | |
|---|---|
| Heat Load (W) | Amount of heat energy produced. Usually defined as:<br>(voltage drop across device) x (current flowing through device) |
| Ambient Temperature (Tamb) | Temperature of air immediately around device to be cooled |
| Maximum Junction Temperature (Tjmax) | Maximum allowable temperature that the device will see at it's silicon junction |
| Thermal Resistance (RΘ) (*C/W) – (Sometimes written as Rth) | The resistance that the heat energy meets in its flow from hot to cold. This is the ratio between the temperature difference and the amount of heat being transferred. –The lower the number, the better it will perform. |
| Junction to Case (RΘjc / Rthjc) | Thermal resistance of the electronic device from the silicon junction to the case of the package (supplied by manufacturer) |
| Case to Sink (RΘcs / Rthcs) | Thermal resistance of the interface material used |
| Sink to Ambient (RΘsa / Rthsa) | Thermal resistance of the heat sink |

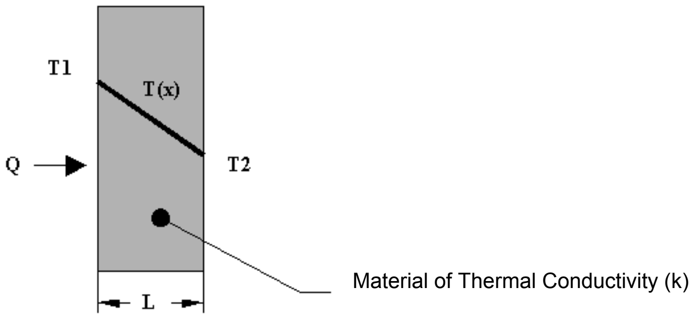
# Modes of Heat Transfer

There are 3 modes of heat transfer:

1. ***Conduction***
2. ***Convection***
3. ***Radiation***

## *1. Conduction*

Conduction is the transfer of heat energy through or across a medium.



$$\boxed{Q = \frac{kAc}{t}(T_1 - T_2)}$$

Where,

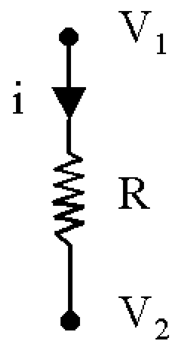
Q = heat (watts)
k = thermal conductivity (watt/m °C)
Ac = contact area (m$^2$)
T = temperature (C)
T = material thickness or length that the heat has to travel (m)

$$\boxed{Q = \frac{kAc}{t}(\Delta T)}$$

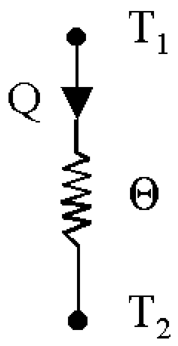
- If holding $\Delta$***T and t***, then Q is ***directly*** proportional to ***Ac***
- If holding $\Delta$***T and Ac***, then Q is ***inversely*** proportional to ***t***
- If holding ***Ac and t***, then Q is ***directly*** proportional to $\Delta$***T***

## (i) Circuit Analysis

**Electrical** **Thermal**



$$\boxed{i = \frac{V_1 - V_2}{R}}$$



$$\boxed{Q = \frac{T_1 - T_2}{\Theta}}$$

## (ii) Conduction Resistance

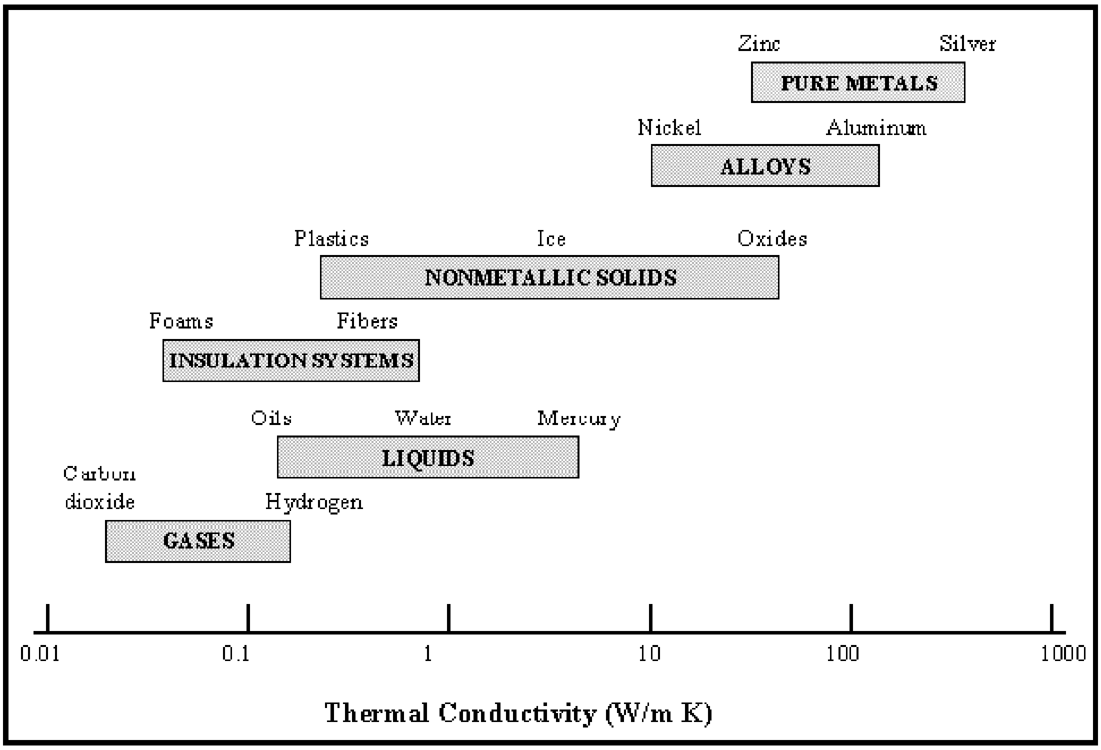
$$\boxed{\Theta = \frac{t}{kAc}}$$

| Material | t (in.) | k(W/m°C) | θ for a TO-220 (°C/W) |
|---|---|---|---|
| **Air** | n/a | 0.026 | n/a |
| **Grease** | 0.002 | 0.197 | 1.67 |
| **Silicon rubber** | 0.005 | 0.472 | 1.74 |
| **Graphoil** | 0.005 | 2.205 | 0.37 |
| **Alumina** | 0.002 | 34.25 | 0.02 |

| Heat Sink Material | k(W/m°C) | Usage |
|---|---|---|
| **Aluminum (1100 series)** | 203 | Stampings |
| **Aluminum (5000 series)** | 202 | Self-Clipping Stampings |
| **Aluminum (6000 series)** | 207 | Extrusions |
| **Copper (110 Alloy)** | 358 | Heat Spreader |

## (iii) Thermal Conductivity (k)

Range of thermal conductivity for various states of matter at normal temperatures and pressure.

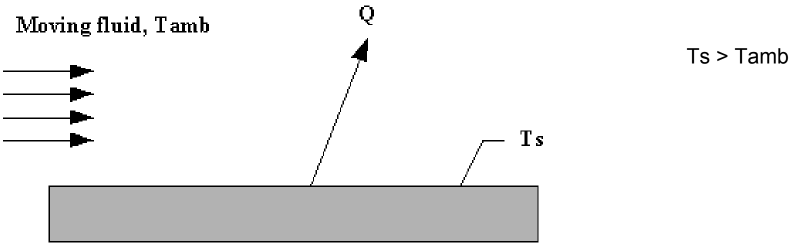


## (iv) Application Tips for Conduction

- All interface surfaces should be smooth and flat. Thermal grease or interface pads should be used on all interfaces where possible.
- Semiconductors should be spaced to obtain a uniform power density.
- If part of the equipment enclosure is to be used as a heat sink, make sure that its materials thickness and interface areas are adequate to handle the expected power density.

## 2. Convection

Convection is the transfer of heat energy from a hot surface to a moving fluid (air, water, etc.) at a lower temperature. It is the most difficult heat transfer mode to mathematically predict.



$$\boxed{Q = h_c A_s (T_s - T_a)}$$

$$\boxed{\Theta = \frac{1}{hcAs}}$$

Q = heat (watts)
hc = heat transfer coefficient (watt/m$^2$ °C)
As = surface area (m$^2$)
Ts = surface temperature (C)
Ta = ambient temperature (C)
$\theta$ = thermal resistance (°C/watt)

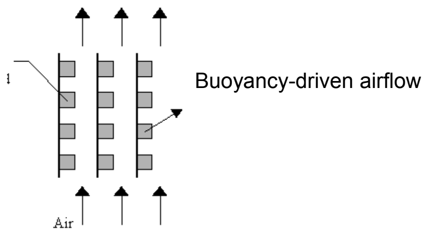
There are two types of convection:

- ***a) Natural Convection***
- ***b) Forced Convection***

## a) Natural Convection

Natural Convection is the fluid flow induced by buoyant forces, which arise from different densities, caused by temperature variations in the fluid. In a properly designed natural convection heat sink operating at sea level conditions, approximately 70% of the heat is transferred by natural convection and 30% by radiation.

At higher altitudes the convection contribution becomes less as the air becomes less dense (ex. @ 70,000 ft., 70%-90% of heat dissipation is by radiation)



### Application Tips for Natural Convection

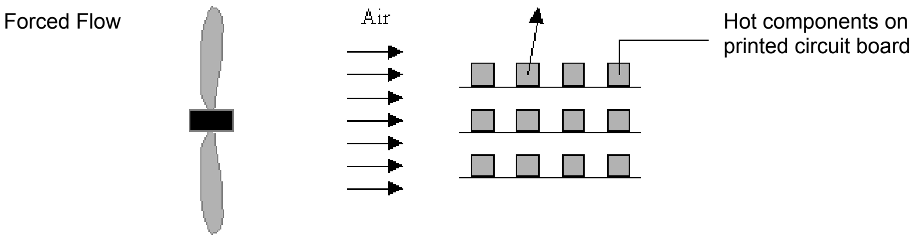
1. Cabinets and racks should be adequately vented at the top and bottom of the enclosure.
2. When racking equipment of different lengths avoid placing short heat-generating packages below longer pieces of equipment.
3. Heat generating devices should be placed near the top of the cabinet while cooler, heat-sensitive components should be located lower in the cabinet.
4. When racking many circuit boards, which will dissipate a significant amount of heat, it is better to place the boards in the vertical position to facilitate convection cooling.
5. Fins on extruded heat sinks should be vertically aligned when natural convection cooling is used.

## *b) Forced Convection*

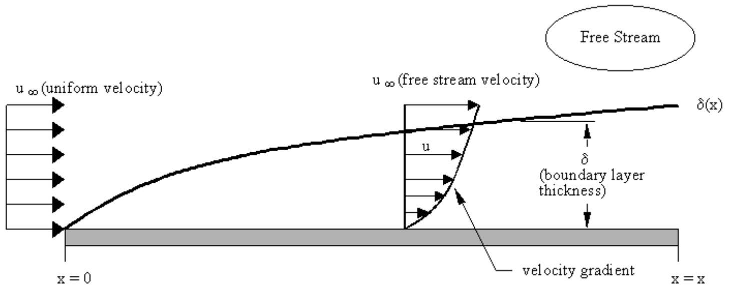
Forced Convection is the ffluid flow caused by external means (e.g. fans, pumps, etc.)

For example, at 180LFM, radiation heat transfer is reduced to a mere 2%-7%; therefore surface treatment (anodizing) is not an important thermal performance factor. Unfinished aluminum is as effective as an anodized finish, due to a lower heat sink temperature and greater convection contribution.

At sea level, radiation heat transfer is usually disregarded because of its relatively small contribution.

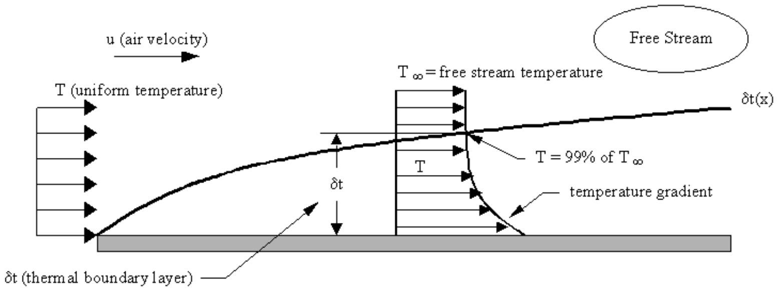


## Velocity Boundary Layer on a Flat Plate



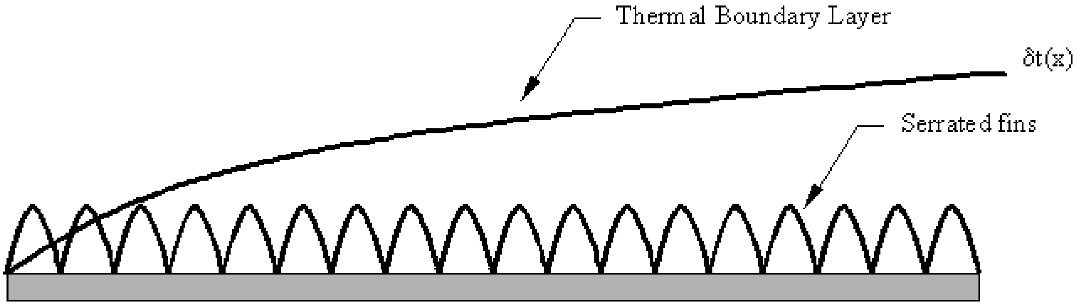
- δ increases as x (distance from leading edge) increases
- δ decreases as the velocity increases

## Thermal Boundary Layer on an isothermal flat plate

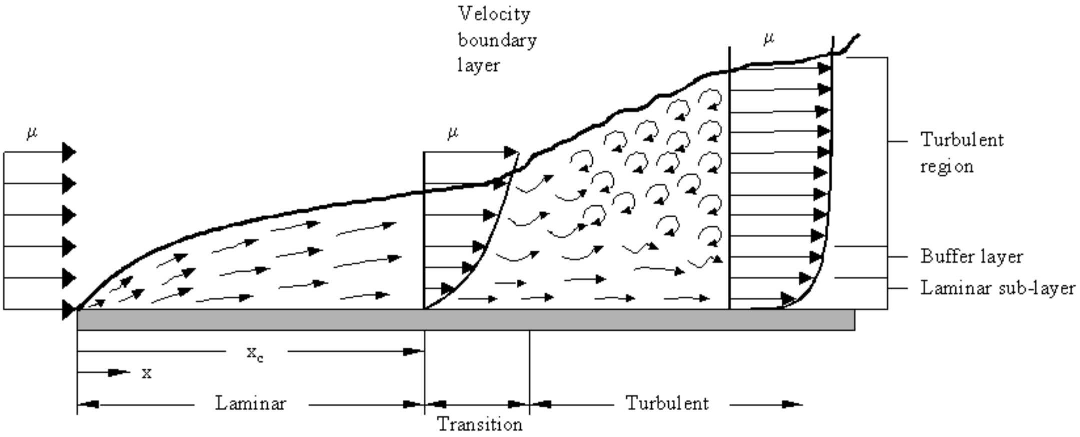


- Temperature gradient decreases as x (distance from leading edge) increases
- δ increases as x (distance from leading edge) increases
- (this explains why serrated fins DON'T work)
- δ is thicker than the depth of the serrations

## Thermal Boundary Layer vs. Serrated Finned Heat Sink



## Laminar vs. Turbulent Flow Development on a Flat Plate



$x$ = characteristic length; is the distance from the leading edge
$x_C$ = distance at which transition begins (transition begins at the critical Reynolds Number $Re_X$)

• Reynolds number is a dimensionless number, which compares the inertial forces vs. the viscous forces.
• $Re_X$ is known to be $1 \times 10^5$ to $3 \times 10^6$, depending on the surface roughness and turbulence level of the free stream.

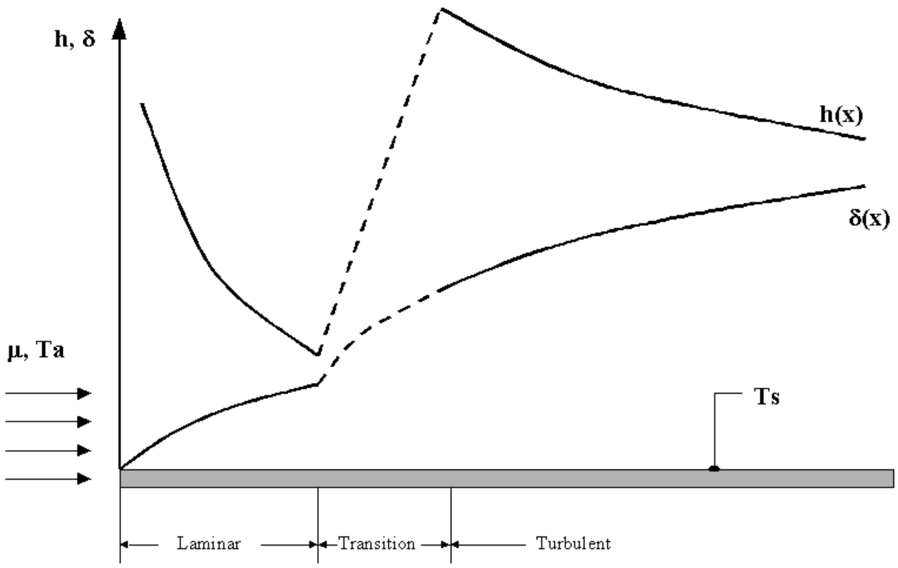
## "h" (convection coefficient)

The convection coefficient, h, is very sensitive to small changes in the following fluid properties:

- Thermal Conductivity
- Dynamic Viscosity
- Density
- Specific Heat
- Velocity
- Flow Type (Laminar or Turbulent)

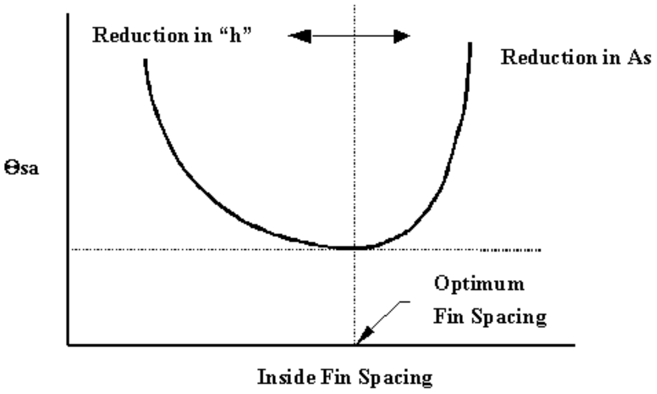
The air-transition usually occurs at about 180 LFM and increases with increased velocity.

# Velocity Boundary Layer Thickness vs. Heat Transfer Coefficient over an Isothermal Flat Plate



## Fin spacing vs. h and A

***h*** is a function of $F_{in}$ Spacing and $F_{in}$ Height. ***$F_{in}$* Spacing** controls free airflow
***$A_s$*** increases as fin spacing decreases.



## Fin Efficiency

•Efficiency, η will ***increase*** if:

- the length of $f_{in}$ decreases
- the thickness of $f_{in}$ increases
- ***"k"*** (thermal conductivity) of $f_{in}$ increases
- ***"h"*** (heat transfer coefficient) decreases - (ie. flow velocity decreases)

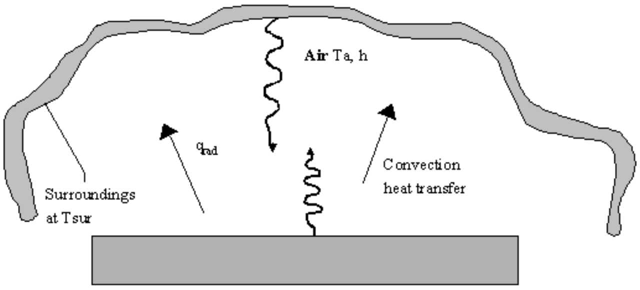
*Note: In forced convection applications, η is desired to be in the 70% range.*

## Application Tips for Forced Convection

1. Board-mounted hat sinks should be staggered so that airflow passes over all of them.
2. Care should be taken not to block the flow of air to heat sinks.
3. Forced-air cooling should be arranged to follow natural-convection air paths.

# 3. Radiation

Radiation is the transfer of heat energy in the form of electromagnetic waves between two surfaces at different temperatures. It is most efficient when in a vacuum.



Surface of emissivity ε and area A at a temperature Ts

## Terms and Definitions

| | |
|---|---|
| Emission | The process of radiation production by matter at a finite temperature |
| Absorption | The process of converting radiation intercepted by matter to internal thermal energy |
| Blackbody | The ideal emitter and absorber. |
| Emissivity | Ratio of the radiation emitted by a surface to the radiation emitted by a blackbody at the same temperature. |

## Radiation - (Stefan-Boltzmann Equation)

$$Q = \varepsilon\sigma Ar(Ts^4 - Ta^4)$$

$$hr = \varepsilon\sigma\,(Ts + Ta)(Ts^2 - Ta^2)$$

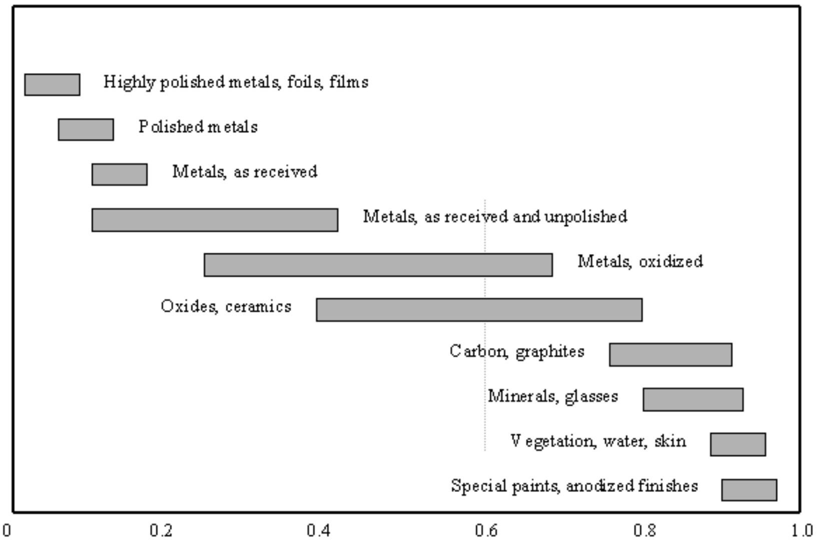
$$\Theta = \frac{1}{hrAr}$$

Where,

Q = heat (watts)
ε = emissivity
Ar = radiative surface area ($m^2$)
Ts = surface temperature (K)

θ = thermal resistance (°C/watt)
σ = Stefan-Boltzmann Constant ($5.67x10^{-8}$ watt/$m^2K^4$)
Ta = ambient temperature (K)
hr = radiative heat transfer coeffecient. (Watt/m2K)

## “ε” Emissivity



Emissivity values for various surfaces

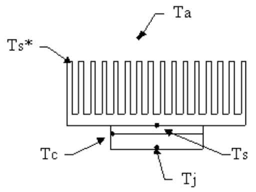
## Typical Emissivity of Various Surfaces

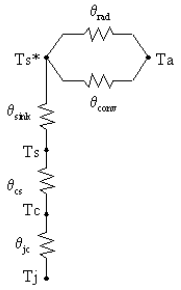
| Material and Finish | Emissivity |
|---|---|
| Aluminum – polished | 0.04 |
| Aluminum – rough | 0.06 |
| Aluminum - anodized (any color) | 0.8 |
| Copper - commercial polished | 0.03 |
| Copper – machined | 0.07 |
| Copper - thick oxide coating | 0.78 |
| Steel - rolled sheet | 0.55 |
| Steel - oxidized | 0.78 |
| Stainless Steel - alloy 316 | 0.28 |
| Nickel Plate - dull finish | 0.11 |
| Silver – Polished | 0.02 |
| Tin – bright | 0.04 |
| Paints & Lacquers - any color - flat finish | 0.94 |
| Paints & Lacquers - any color - gloss finish | 0.89 |

## Application Tips for Radiation

1. Maximize surface emissivity
2. Maximize unobstructed exposed surface area
3. The only radiative surfaces are those in plain view (not total surface area). The area between fins radiates into each other.
4. Use high conductivity heat sink and interface materials to minimize thermal resistance from case to radiating surface and increase the temperature difference between dissipating surface and ambient air molecules.

## Removing Heat from a Semiconductor





$$\Theta ja = \Theta jc + \Theta cs + \Theta sa$$

$$\Theta ja = \frac{Tj - Ta}{Q}$$

$$\Theta jc = \text{junction} - \text{to} - \text{case}$$

$$\Theta cs = \text{case} - \text{to} - \text{sink}$$

$$\Theta sa = \text{sink} - \text{to} - \text{ambient}$$

$$\Theta sa = \frac{(\Theta conv)(\Theta rad)}{(\Theta conv + \Theta rad + \Theta sink)}$$

## Selecting the Correct Heat Sink

There following parameters are necessary to determine the required heatsink:

1. Q - Amount of heat (W)
2. $Tj_{max}$ - maximum allowable junction temperature (°C), supplied by the manufacturer
3. Ta - ambient fluid temperature (°C)
4. Rθjc - thermal resistance of the device, supplied by the manufacturer
5. Rθcs - thermal resistance of the interface material
6. Thermal resistivity (ρ), thickness (t) and contact area (A) ⟶
7. Natural or forced convection cooling
8. Air flow (LFM) (If forced convection)

$$\boxed{\Theta cs = \frac{(\rho)(t)}{A}}$$

$$\Theta ja = \Theta jc + \Theta cs + \Theta sa$$

$$\Theta sa = \Theta ja - (\Theta jc + \Theta cs)$$

$$\Theta ja = \frac{(Tj - Ta)}{Q}$$

$$\boxed{\Theta sa = \frac{(\overset{\checkmark}{Tj} - \overset{\checkmark}{Ta})}{\checkmark\, Q} - (\overset{\checkmark}{\Theta jc} + \overset{\checkmark}{\Theta cs})}$$

## Example

A TO-220 package outline device is dissipating 4 watts (Q), the Tj =150°C, and Ta = 50°C. Rθjc = 3.0 °C/W (which is taken from the device’s data sheet)

Therefore the Thermal resistance of heat sink ($\Theta_{sa}$) can be calculated:

$$\Theta sa = \frac{(Tj - Ta)}{Q} - (\Theta jc + \Theta cs)$$

Assuming that:

- interface material is silicon grease
- 0.002 inches thick
- 0.36 $in^2$ contact area

The thermal resistance of Silicon grease can be found to be at:

θcs = **1.13°C/W**

*Therefore:*

$$\Theta_{sa} = \frac{(150 - 50)}{4} - (3.0 + 1.3)$$

**θsa = <u>20.87°C/W</u>** or **temperature rise = <u>83.48°C</u>** [@ 4 Watts (θsa*Q)]

*Therefore:*

A heat sink will be required with a thermal resistance or temperature rise less than or equal to 20.87°C/W or 83.48°C respectively.

## Extrusion Data

<u>60270</u>

<u>4.7</u> in2/in

<u>0.2</u> lb./ft

<u>14.9</u>°C/W/3in.

### Terms and Definitions

| | |
|---|---|
| 60270 | The extrusion's 5 digit base part number |
| in2/in | The perimeter of the cross-sectional profile of the extrusion is also the outside surface area per inch of length. This is used to predict the thermal resistance (θsa) using the performance factor table. |
| lb/ft | Weight of extrusion per foot. |
| °C/W/3in | The theoretical thermal resistance (°C/W) for a 3 inch long piece in Natural Convection. This is a calculated number based on the following assumptions:<br>- sink-to-ambient ΔT = 75°C<br>- black anodized finish<br>- single point heat source at the center of the 3 inch section |

## Temperature Correction Factors

## Natural Convection

As ∆T decreases, the heat sink efficiency decreases.

Therefore:

***Correct (°C/W/3in) = (Temperature Correction) x (Published °C/W/3in)***

| **Temperature Rise (∆Tsa)** | **Correction Factor** |
|---|---|
| 75°C | 1 |
| 70°C | 1.017 |
| 60°C | 1.057 |
| 50°C | 1.106 |
| 40°C | 1.17 |
| 30°C | 1.257 |

## Length Correction Factors

## Published Thermal Performance:

- Natural Convection
- 3 inch long piece
- Centrally located point source heat load

**Therefore**:

***(Length Correction) x (Published °C/W/3in) = Correct (°C/W)***

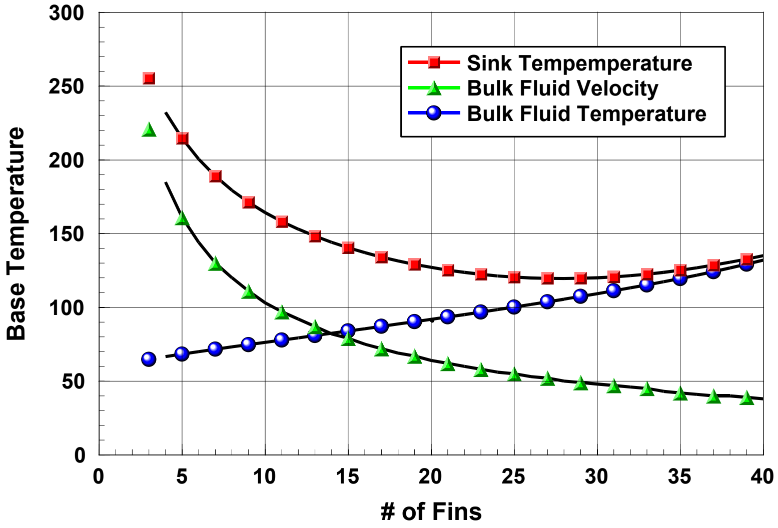
| **Length** | **Correction Factor** |
|---|---|
| 1 | 1.8 |
| 2 | 1.25 |
| 3 | 1 |
| 4 | 0.87 |
| 5 | 0.78 |
| 6 | 0.73 |
| 7 | 0.67 |
| 8 | 0.64 |
| 9 | 0.6 |
| 10 | 0.58 |
| 11 | 0.56 |
| 12 | 0.54 |
| 13 | 0.52 |
| 14 | 0.51 |
| 15 | 0.5 |

# Thermal Modelling Capabilities

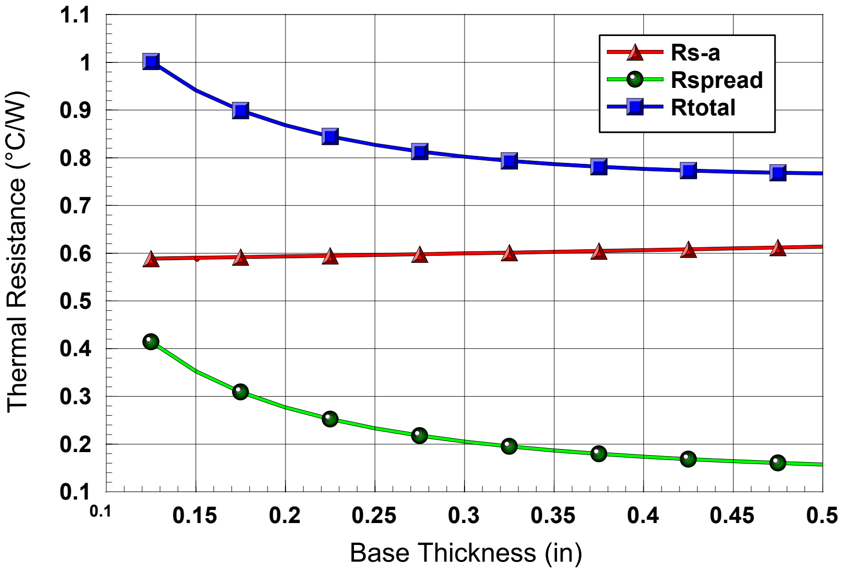
## Parametric thermal Analysis

1. Natural Convection
2. Forced Convection
3. Spreading Resistance
4. Transient Analysis
5. Cold Plate Analysis

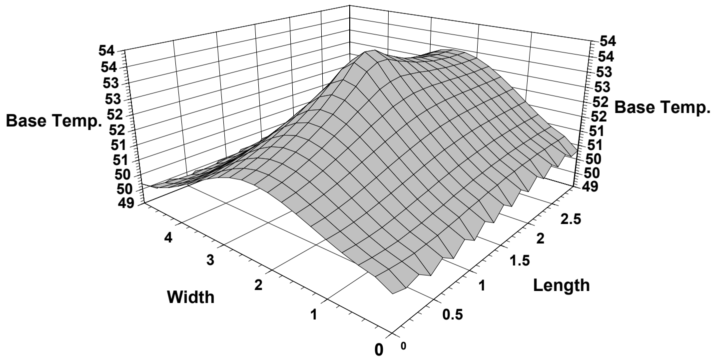
## Natural Convection Analysis



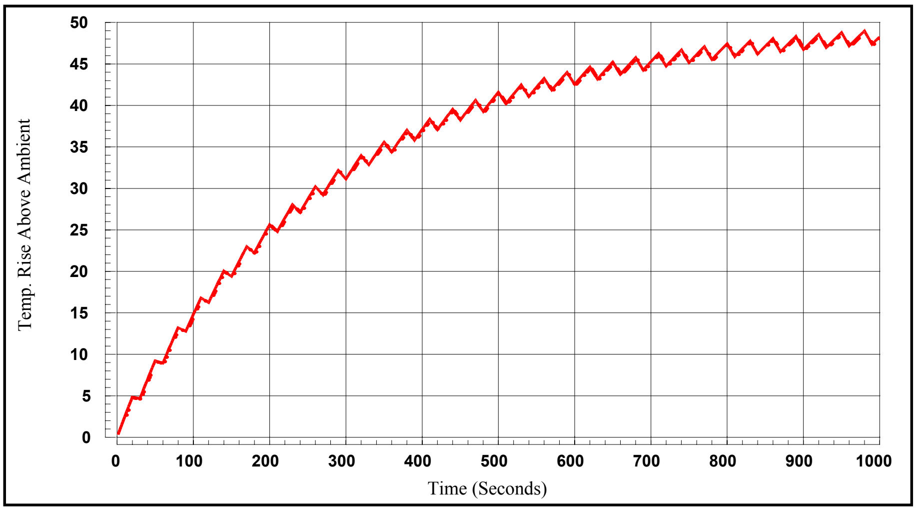
## Forced Convection w/Spreading at Given Airflow



## Spreading Resistance on a Plate 15 watts centered on a plate



## Transient Analysis Duty Cycle

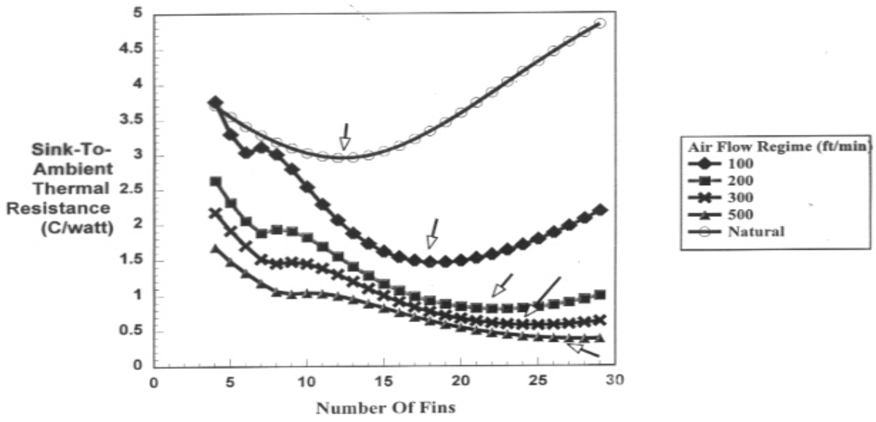


*(0.5°C/W, 1.5 lbs., 150W on for 20sec. And 0 watts for 10 sec. 1000 seconds)*

## Optimized Design

FIN OPTIMIZATION FOR VARIOUS AIR FLOWS

Heat Sink Size is 4 x 4 x 1.0 with 1/4" Shroud



## Reference

“Aavid Thermalloy Thermal Seminar,” Mustafa, S., El Segundo, CA, November 2002.