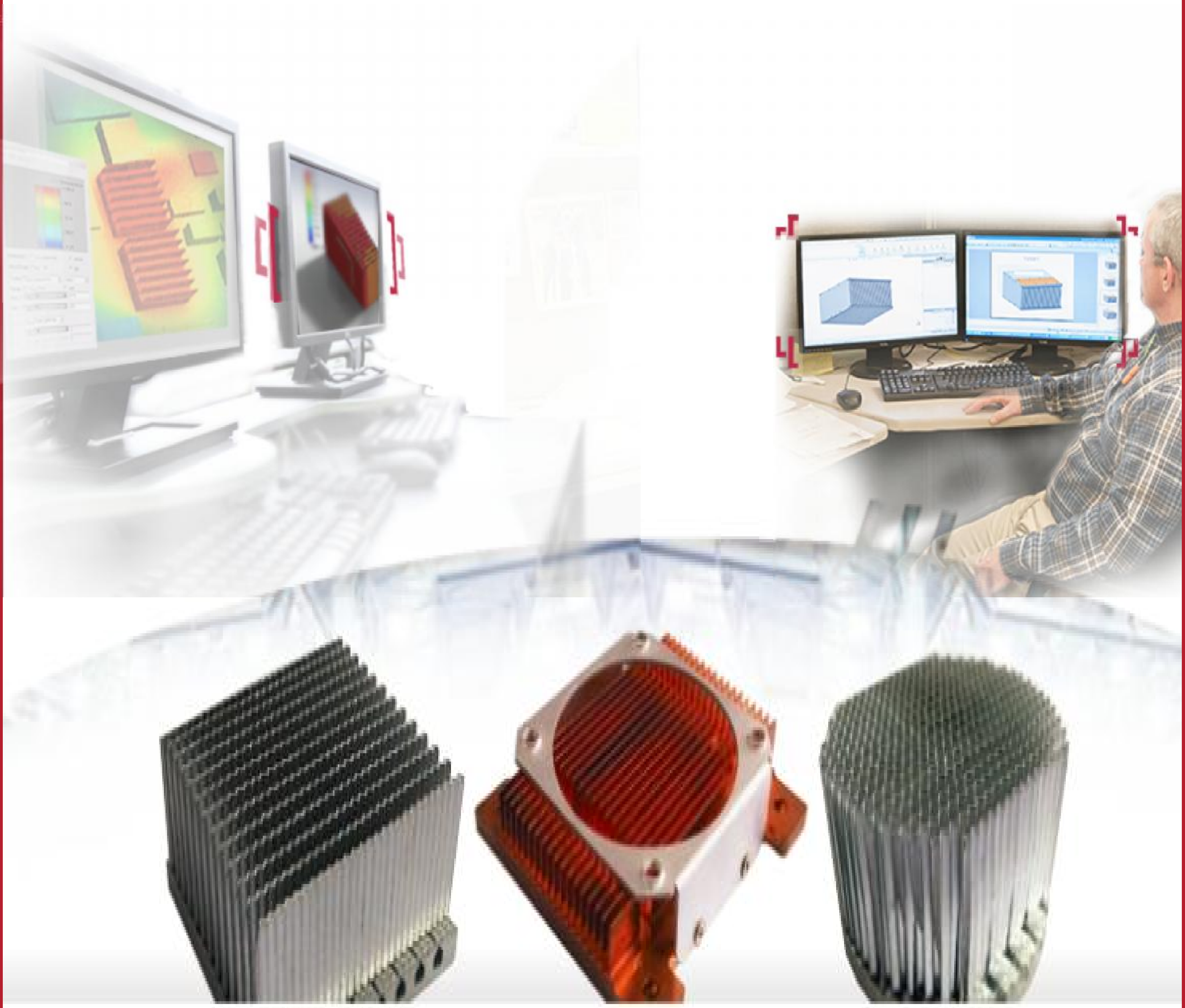
TECHNICAL BRIEF

wakefield-vette

HEAT SINK DESIGN FACTS & GUIDELINES FOR THERMAL ANALYSIS



Thermal Cooling Solutions from **Smart** to **Finish**

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Heat Sink Design Facts and Guidelines for Thermal Analysis

Topics Covered:

- Introduction
- Maximization of Thermal Management
- Heat Transfer Basics
- Modes of Heat Transfer:
  1. Conduction
  2. Convection
  3. Radiation
- Removing Heat from a Semiconductor
- Selecting the Correct Heat Sink
- Extrusion Data – Published in Catalog
- Temperature and Length Correction Factors
- General Parameters both Natural and Forced Convection
- Conclusion - Relative Heat Sink Cost verses Thermal Performance

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, (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 junction temperature, (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 & Temperature Difference

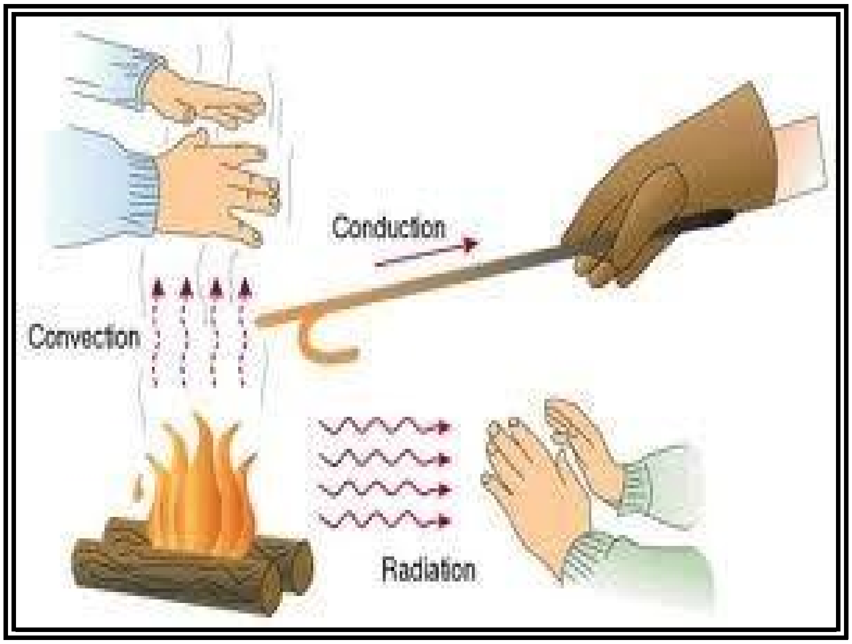
Heat Transfer occurs when two surfaces have different temperatures, thus causing heat energy to transfer from the hotter surface to the colder surface.

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.

Terms and Definitions

- **Heat Load (W) = Amount of heat energy produced - Wattage. Usually defined as: (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), the maximum allowable temperature that the Device will see at its silicon junction**
- **Thermal Resistance (RΘ) (*C/W) – (Sometimes written as Rth) The resistance that the Heat Energy meets as its flows from hot, (Device) to cold, (Ambient).**
- **Junction-to-Case Thermal Resistance, (RΘjc), of the electronic device from the silicon junction to the case of the package (supplied by manufacturer).**
- **RΘcs = Thermal Resistance of the Thermal Interface Material, (TIM), used between Device and Heat Sink**
- **RΘsa = Thermal Resistance of the Heat Sink to the Ambient (surrounding air).**

There are 3 modes of heat transfer:

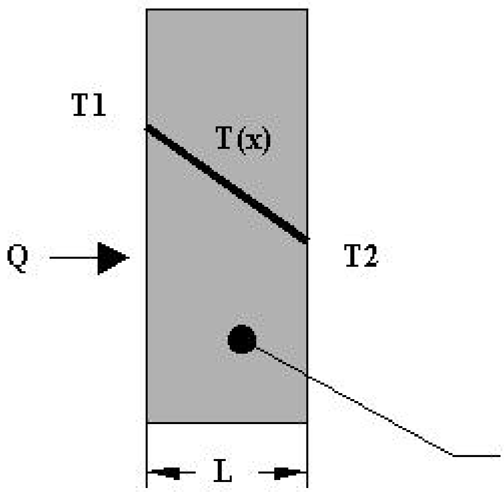


1. Conduction - 2.Convection - 3.Radiation

1. Conduction

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

Material of Thermal Conductivity (k)



Material Thermal Conductivity (k)

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

Where,

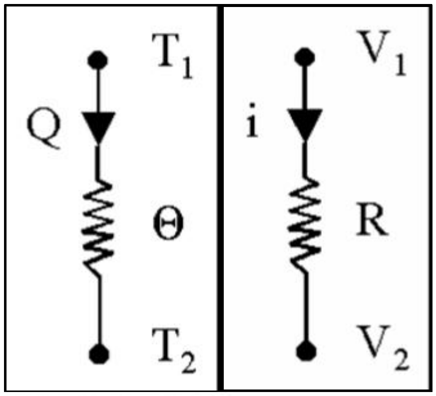
Q = heat (watts)
k = thermal conductivity (watt / m -°C)
Ac = contact area (m^2)
T = temperature (C)
T = material thickness or length that the heat has to travel (m)

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

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

Circuit Analysis

Thermal **Electrical**



$$Q = \frac{T_1 - T_2}{\Theta} \qquad i = \frac{V_1 - V_2}{R}$$

Conduction Resistance

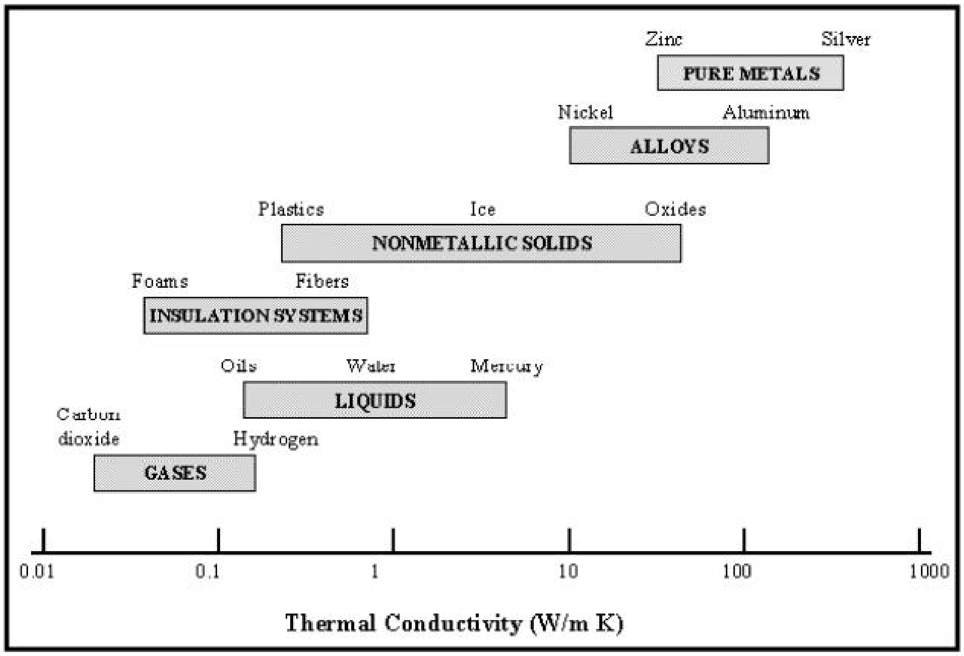
$$\Theta = \frac{t}{kAc}$$

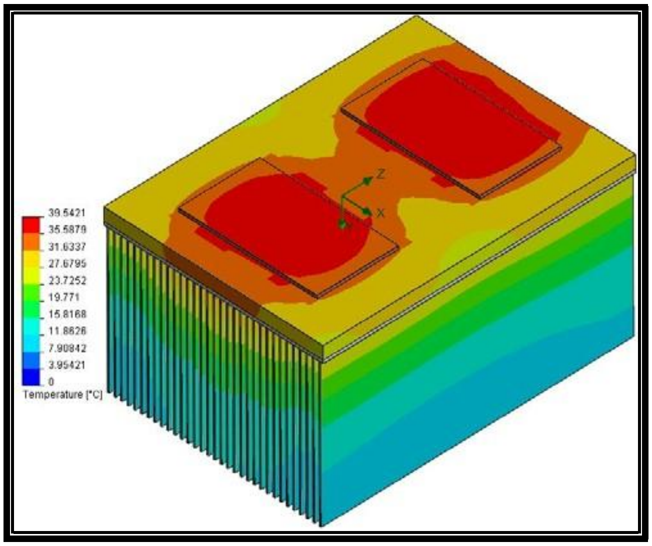
MATERIAL	CONDUCTIVITY	USAGE
(Series/Alloy)	(k(W/mC)	(Product Type)
Al-5052 H36	138	Stampings
Al - 6061 T6	167	Extrusions
Al - 6063 T6	209	Extrusions
Al - 1100 H14	220	Stampings
Cu - CDA110	300	Bonded-Fin
Cu - CDA101	398	Heat Spreaders

Comparison of Materials Used for Heat Sink Manufacturing

Thermal Conductivity (k)

Range of Thermal Conductivity for Various States of Matter at Normal Temperatures and Pressure.



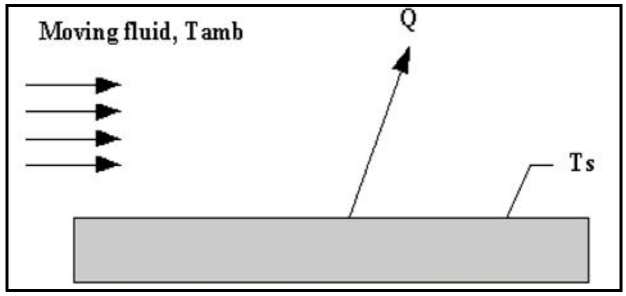


Application Tips for Conduction

1. **All Interface Surfaces should be smooth and flat – i.e. 0.003" to 0.004"/inch.**
2. **Thermal Grease or Thermal Interface Materials – TIMs - should be used between all Thermal Interfaces.**
3. **Semiconductors should be spaced to obtain a uniform 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.



$$Q = h_c A_s (T_s - T_a) \qquad \Theta = \frac{1}{hcAs}$$

Where:

Q = heat (watts)

hc = heat transfer coefficient (watt/m2 °C)

As = surface area (m^2)

Ts = surface temperature (C)

Ta = ambient temperature (C)

θ = thermal resistance (°C/watt)

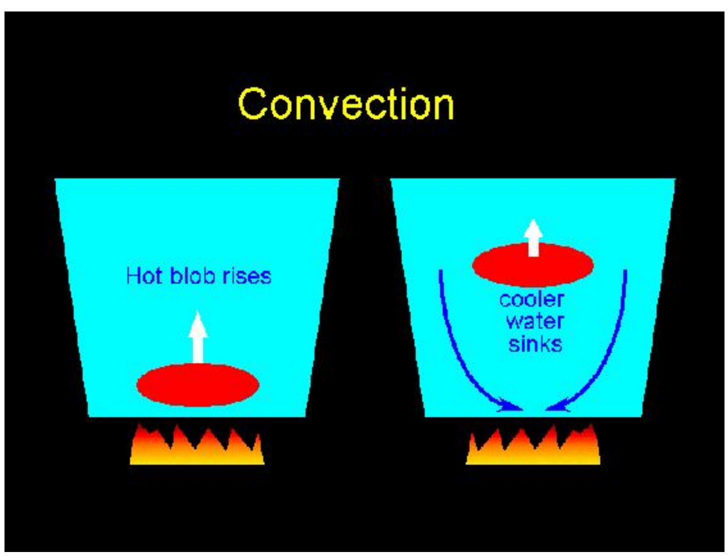
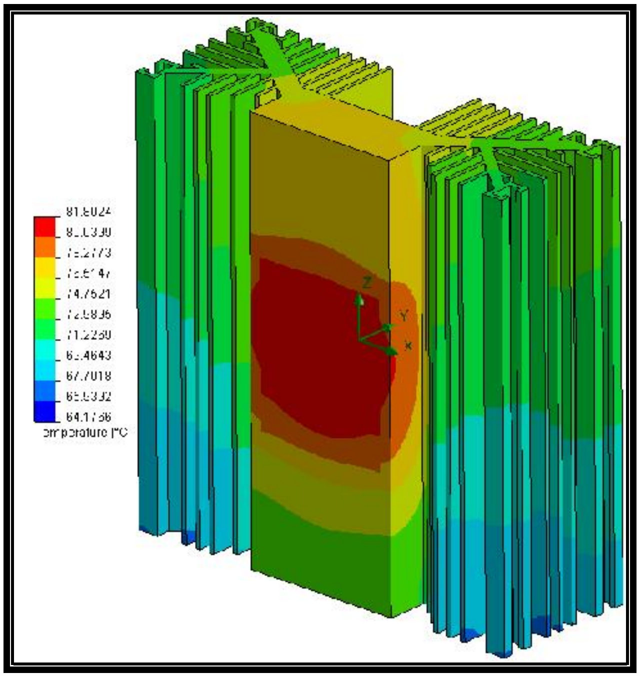


Illustration of Convection Effect – Heated Container of Liquid

A) Natural Convection

Natural Convection is the Air 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

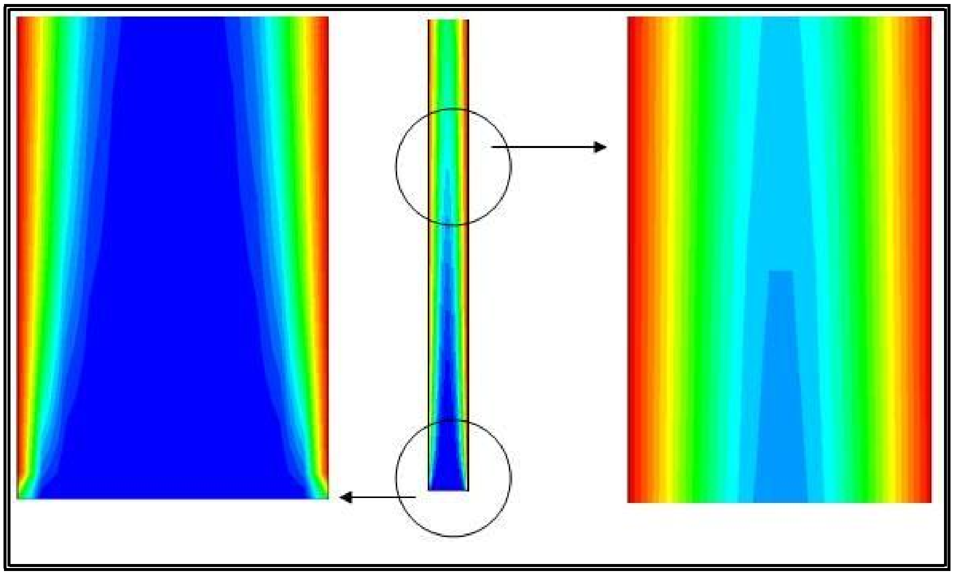
- **Cabinets and racks should be adequately vented at the top and bottom of the enclosure.**
- **When mounting devices of different lengths avoid placing short heat-generating packages below longer pieces of equipment.**
- **Heat generating devices should be placed near the top of the cabinet while cooler, heat-sensitive components should be located lower in the cabinet.**
- **When mounting multiple devices, which will dissipate a significant amount of heat, it is better to place them in the vertical position to facilitate convection cooling.**
- **Fins on extruded Heat Sinks should be** vertically aligned **when Natural Convection cooling is used.**
- **Fin-to-Fin Spacing should typically be greater than ~0.250", (6mm+)**

B) Forced Convection

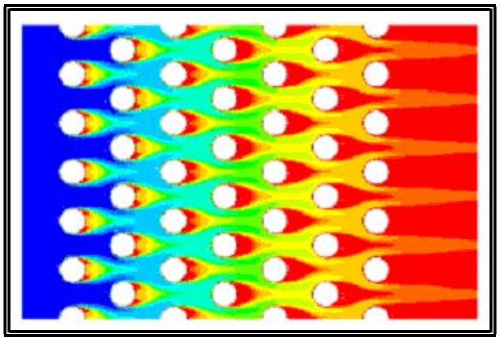
Forced Convection is the Air Flow caused by external means (e.g. fans, pumps, etc.)

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.

Air Flow within a Channel –Between Fins - i.e. boundary layer formation)



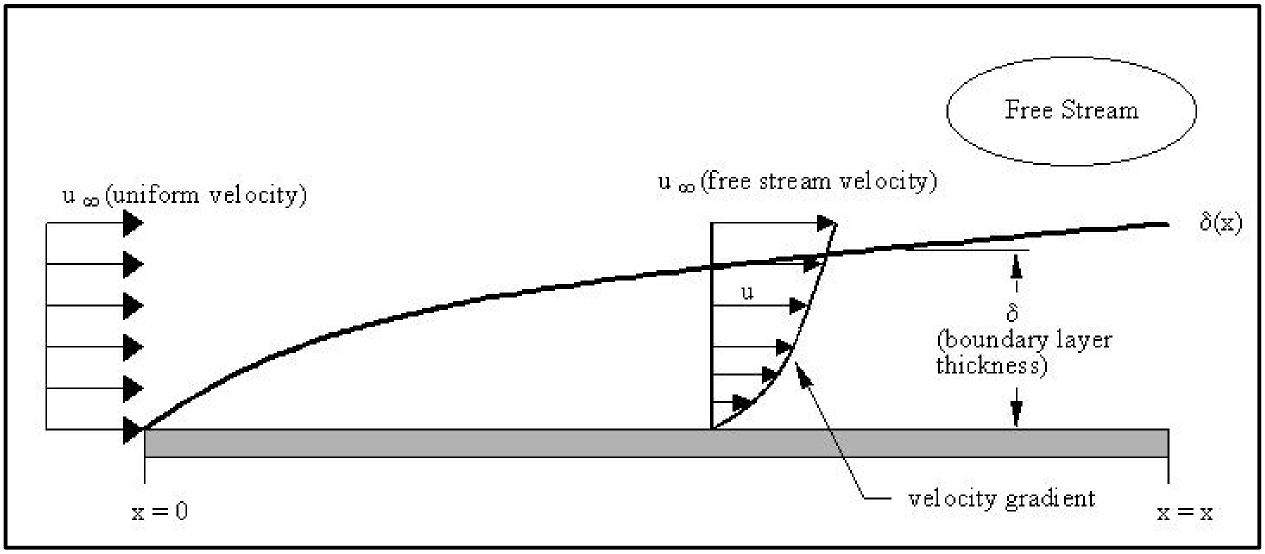
Air Flow Through a Pin-Fin Heat Sink – flow direction "left-to-right"
Blue = High Air Flow and Red = Low Air Flow



Application Tips for Forced Convection

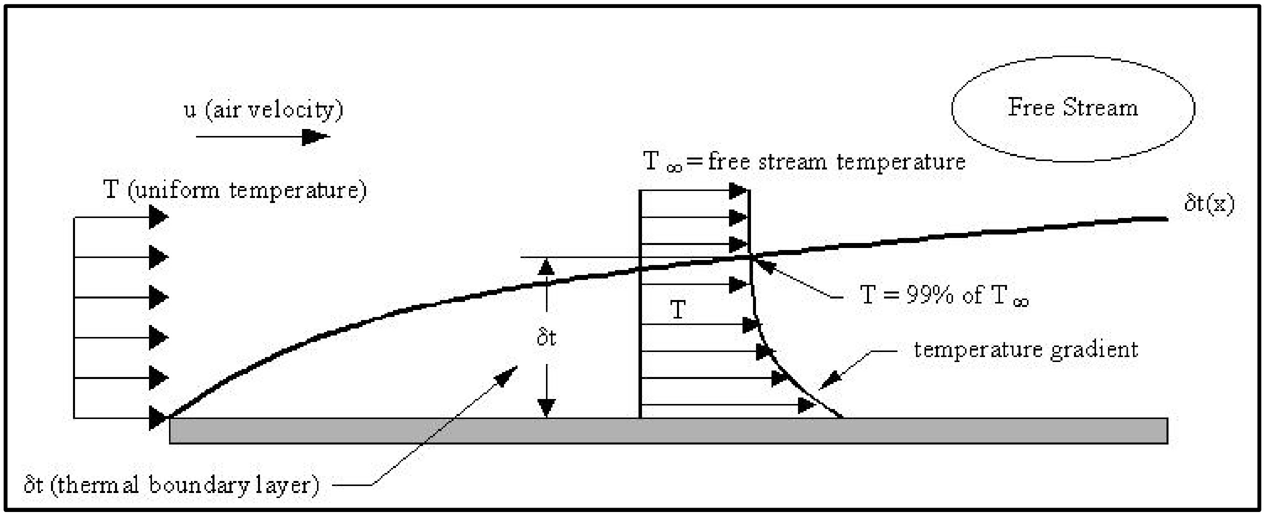
- **Thick Fins – Minimum of 0.080", (2mm) and Greater**
- **High Fin Density - Typically 6 fins/inch – Balance against Pressure Drop**
- **Transition from Extrusion to Bonded-Fin – Consider Copper Option for application with very High Heat Flux**

Velocity Boundary Layer on a Flat Plate



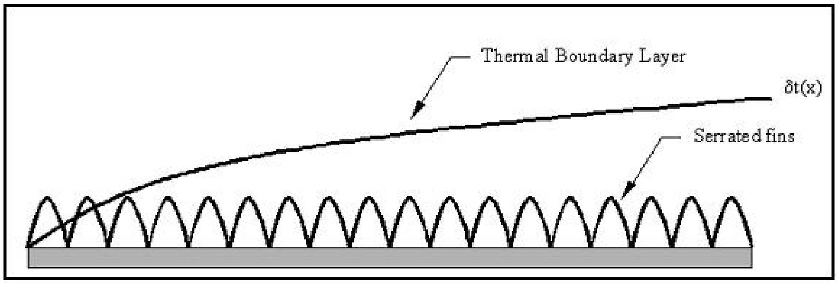
- δ – boundary layer increases as x (distance from leading edge) increases
- δ – boundary layer decreases as the velocity increases

Thermal Boundary Layer on an Isothermal Flat Plate



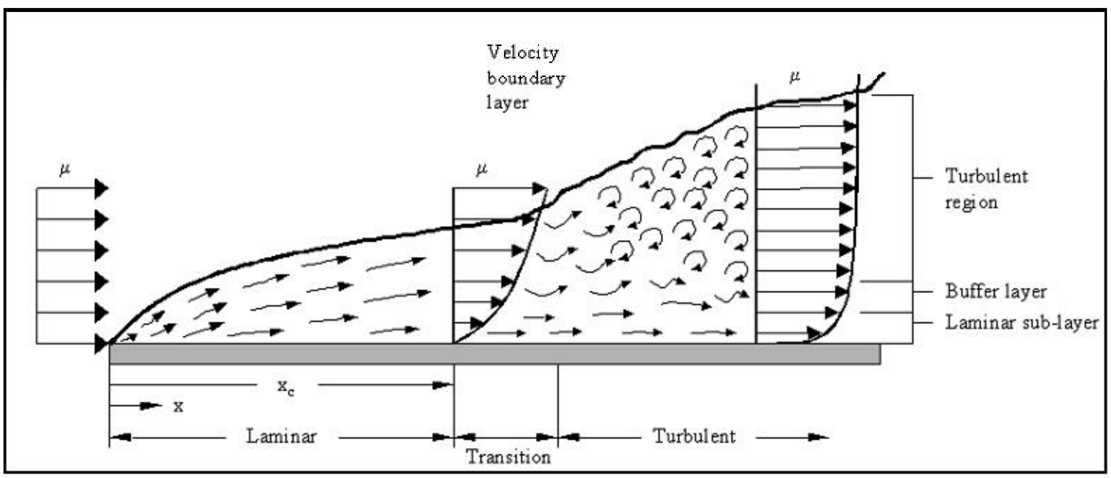
- Temperature gradient decreases as x (distance from leading edge) increases
- δ – boundary layer increases as x (distance from leading edge) increases
- This explains why serrated fins DON'T work
- δ – boundary layer is thicker than the depth of the serrations

Thermal Boundary Layer vs. Serrated Finned Heat Sink



- Increased surface area of the serrated-fin profile never benefits from contact with the ambient air.
- The formation of the Boundary Layer and its physical thickness is the “barrier” preventing the air from contacting the serrated surface.
- Since the ambient air is not contacting the serrated-fin surface it cannot extract the heat by convection.
- Therefore, the additional cost and complexity of adding serrated-fin geometry to a heat sink designed for a Natural Convection application is not justified.

Laminar vs. Turbulent Flow Development on a Flat Plate



Flow Development - Points of Interest:

- x = characteristic length; is the distance from the leading edge
- xc = distance at which transition begins (transition begins at the critical Reynolds Number (Rex)
- Reynolds Number, (Rex), is a dimensionless number, which compares the inertial forces vs. the viscous forces.
- Reynolds Number, (Rex), is known to be 1 x 105 to 3 x 106, depending on the surface roughness and turbulent level of the free stream.

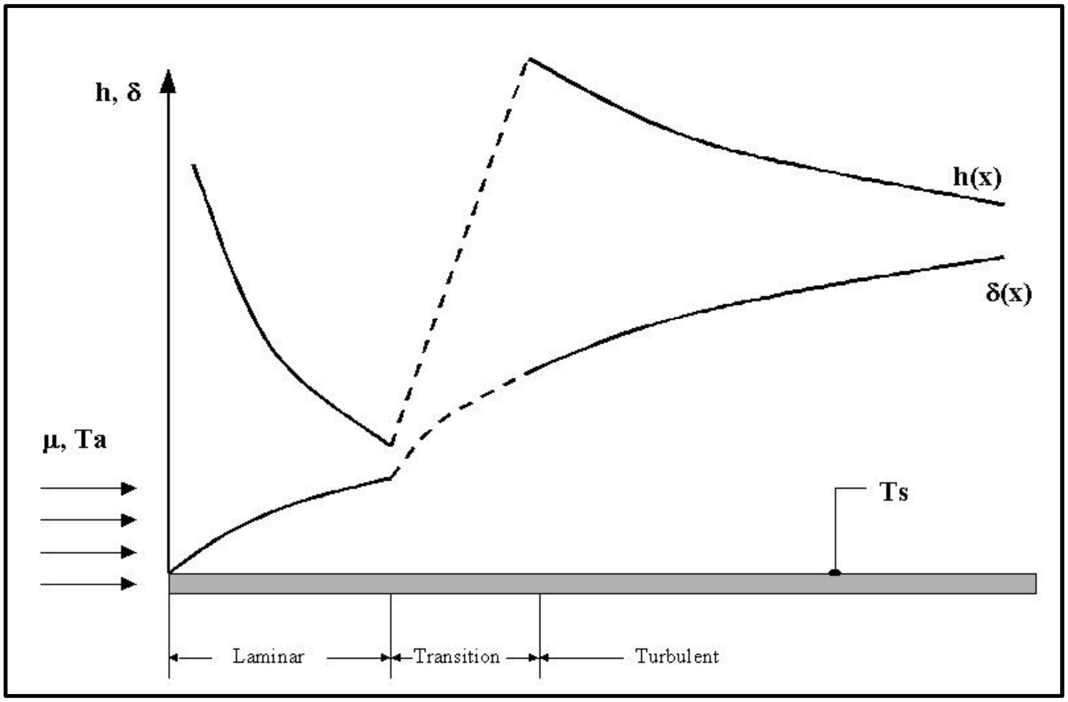
“h” (Convection Coefficient)

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, (from Laminar to Turbulent), usually occurs at about 150-180 LFM and increases with increased velocity.

Boundary Layer Thickness vs. Heat Transfer Coefficient over an Isothermal Flat Plate Relative to Increasing Air Flow



Changing “h” Heat Transfer Coefficient - Points of Interest:

- **Note the dramatic increasing “h” (heat transfer coefficient) in the “Transition Zone”.**
- **This is caused by the turbulent nature of the air molecules “mixing” and removing heat from the surface of the heat sink fins.**
- **Once the Air Flow is established in the Turbulent Region – the “h” gradually decreases due to the establishment of the Laminar Sub-Layer in combination with the Buffer Layers.**

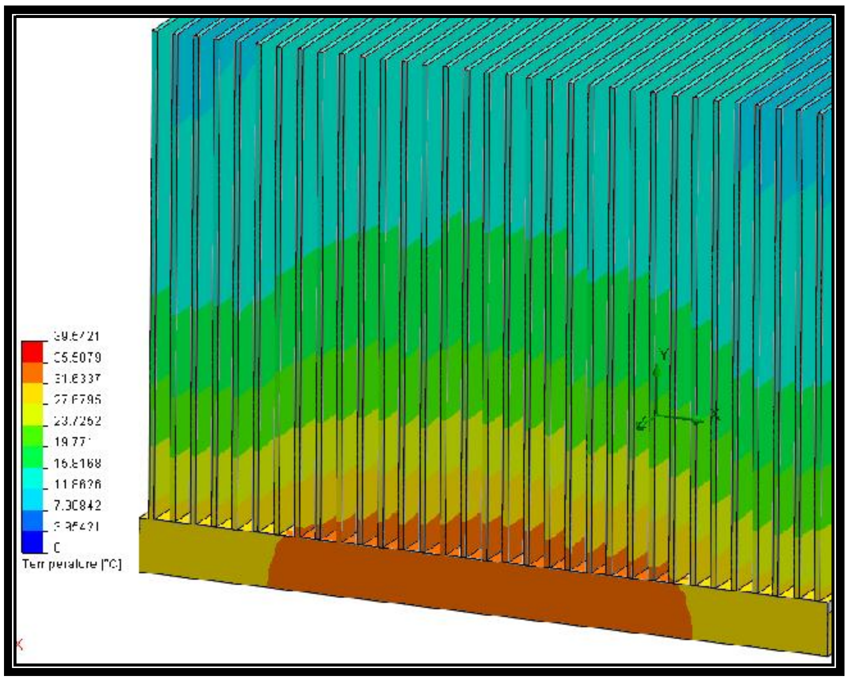
Fin Efficiency

Fin Efficiency, η will *Increase* if:

- **The Length of Fin Decreases**
- **The Thickness of Fin Increases**
- ***"k"* (Thermal Conductivity) of Fin Increases**
- ***"h"* (Heat Transfer Coefficient) Decreases –**

  (i.e. Air Flow Velocity Decreases)

Note: In forced convection applications, η is desired to be in the 40-70% range.

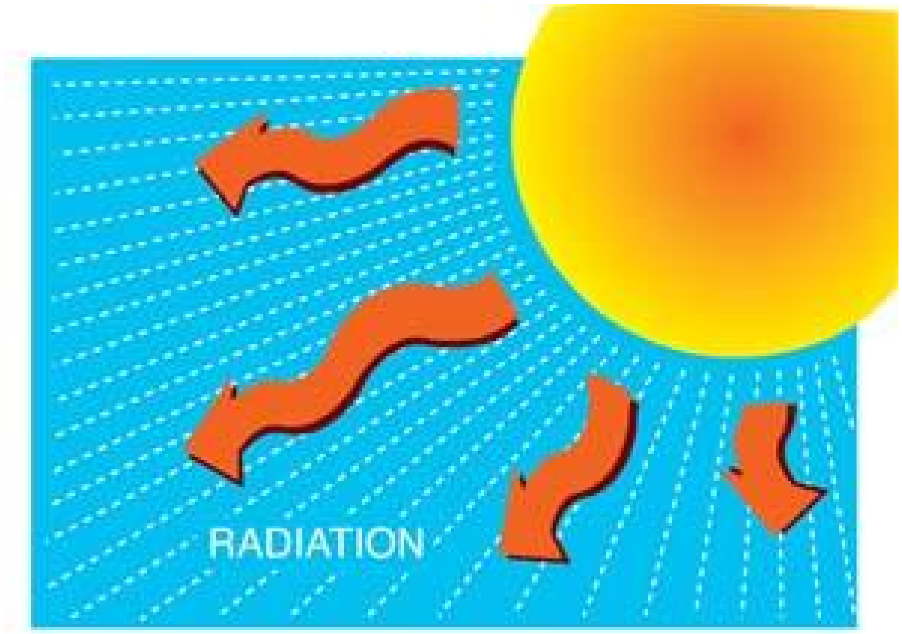


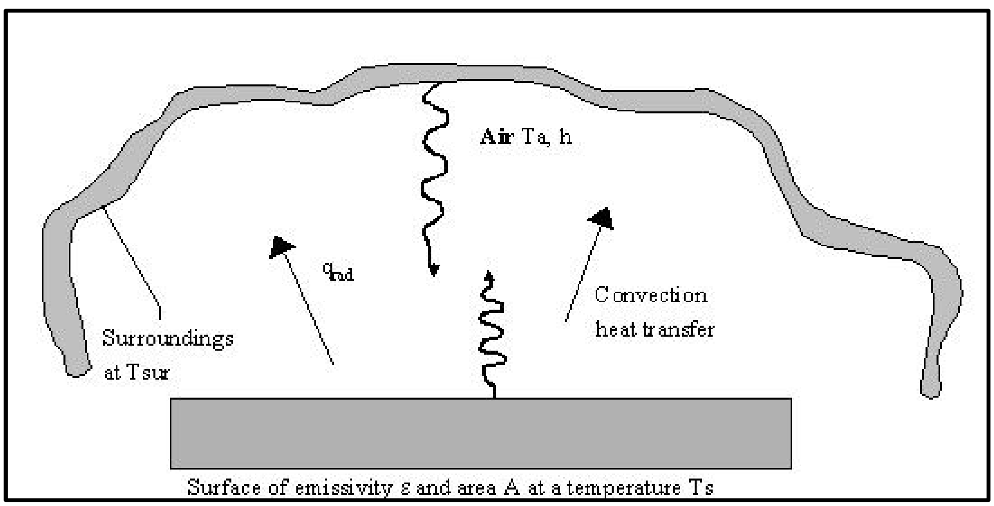
Application Tips for Forced Convection

1. **Board-mounted heat sinks should be "staggered" so that Air Flow passes over all of them.**
2. **Care should be taken not to block the Air Flow to heat sinks.**
3. **Forced-Air cooling should be arranged to follow Natural-Convection air paths.**
4. **General Rule Natural Convection use Thin Fins – ~0.050"-0.060" Thickness**
5. **General Rule Forced Convection use Thicker Fins - ~0.060"-0.100" Thickness**
6. **Consider Adding Serrated-Fins to Increase Surface Area and Reduce Heat Sink Thermal Resistance – Increases of 20-30% can typically be achieved.**

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.





Radiation - Terms and Definitions

EMISSION	The Process of Radiation 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 R - (Stefan-Boltzmann Equation)

$$Q = \varepsilon\sigma A_r (T_s^4 - T_a^4)$$

$$h_r = \varepsilon\sigma (T_s + T_a)(T_s^2 - T_a^2)$$

$$\Theta = 1 / h_r A_r$$

Where,

Q = heat (Watts)

ε = emissivity

Ar = radiative surface are (m^2)

Ts = surface temperature (°K)

θ = thermal resistance (°C/watt)

σ = Stefan-Boltzmann Constant (5.67x10-8 watt/m^2K4)

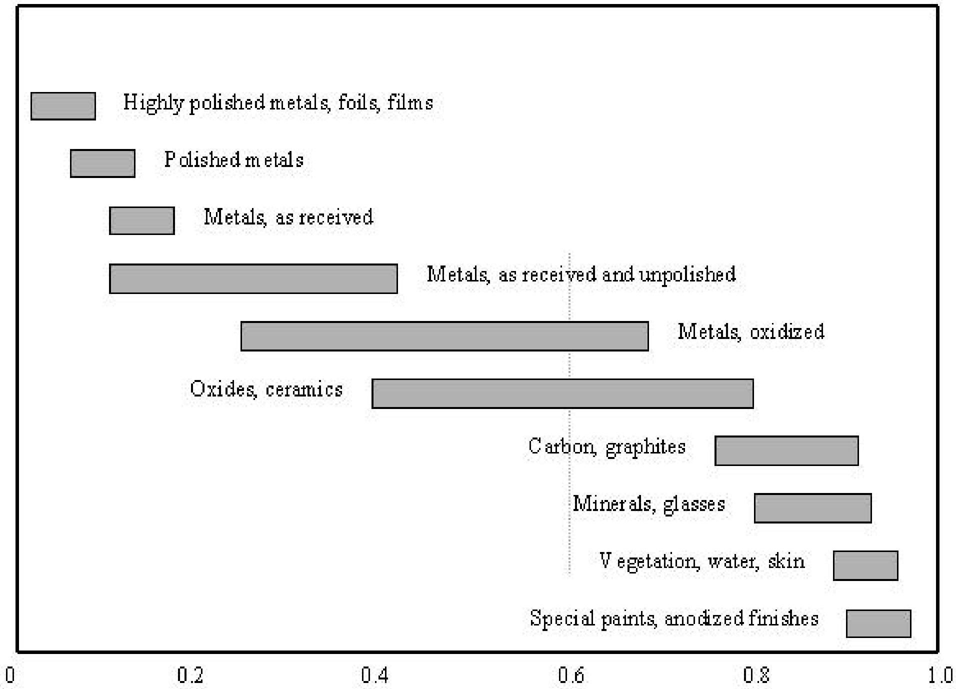
Ta = ambient temperature (K)

hr = radiative heat transfer coefficient. (Watt/m^2K)

Application Tips for Radiation

- Maximize surface emissivity.
- Maximize unobstructed exposed surface area.
- The only radiative surfaces are those in plain view, (not total surface area).
- The area between fins radiates into each other.

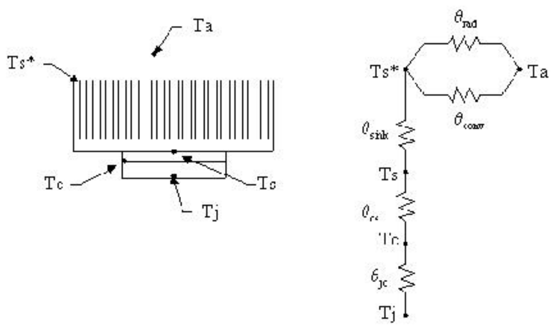
Approximate Values of “ε” Emissivity



Emissivity values for various surfaces

Material & Finish	Emissivity
Aluminum - Polished	0.04
Aluminum - Extruded	0.06
Aluminum - Anodized	0.80
Copper - Polished	0.03
Copper - Machined	0.07
Copper - Oxidized	0.78
Steel - Rolled Strip	0.55
Steel - Oxidized	0.78
Stainless Steel - A316	0.28
Nickel Plate - Dull	0.11
Tin - Bright Plate	0.04
Paint - Gloss Finish	0.89
Paint - Flat Finish	0.94

Removing Heat from a Semiconductor



$$\Theta_{ja} = \Theta_{jc} + \Theta_{cs} + \Theta_{sa}$$

$$\Theta_{ja} = \frac{T_j - T_a}{Q}$$

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

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

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

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

Selecting the Correct Heat Sink …

The following parameters are necessary to determine the required heat sink:

1. **Q - Amount of Power, (heat = (W)), to be dissipated**
2. **Tjmax - Maximum allowable Junction Temperature (°C)**
3. **Ta – Ambient Temperature of the surrounding fluid, (Air), (°C)**
4. **Rθjc - Thermal Resistance of the device "junction-to-case"**
5. **Rθcs - Thermal Resistance of the Thermal Interface Material, (TIM)**
6. **Thermal resistivity (ρ), thickness (t) and contact area (A)**
7. **Natural or Forced Convection Cooling**
8. **Air flow – Linear Feet per Minute, (LFM), (If Forced Convection)**

$$\Theta_{ja} = \Theta_{jc} + \Theta_{cs} + \Theta_{sa}$$

$$\Theta_{sa} = \Theta_{ja} - (\Theta_{jc} + \Theta_{cs})$$

$$\Theta_{ja} = \frac{(T_j - T_a)}{Q}$$

$$\Theta_{sa} = \frac{(T_j - T_a)}{Q} - (\Theta_{jc} + \Theta_{cs})$$

Heat Sink Selection - Example:

- **TO-220 package outline device is dissipating 7 watts (Q)**
- **The Maximum Junction Temperature, is Tj = 125°C**
- **And the Maximum Ambient Temperature, is Ta = 65°C**
- **Component Junction-to-Case Thermal Resistance, is Rθjc = 2.5 °C/W (Note: this information can be obtained from the device's data sheet).**

Assuming that:

- **Interface material is Silicon Grease – Wakefield 120 Series**
- **0.002 inches thick**
- **0.36 in2 contact area**

The Thermal Resistance of Silicon Oil-Based Grease can be found to be as: Thermal Resistivity, (ρ), (120 Series = 56 C-in/W), thickness, (t), (in) and contact area, (A), (in^2)

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

θcs = 56 C-in/W x 0.002 in / 0.36 in^2 = 0.311°C/W

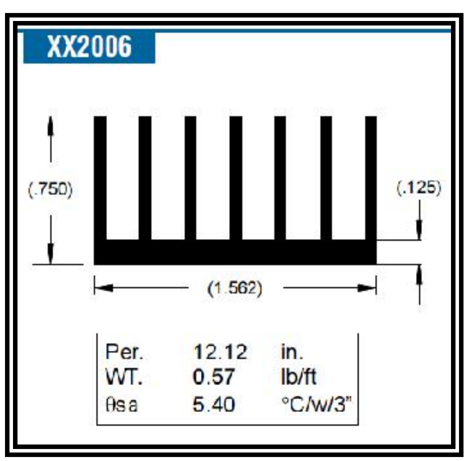
Θsa = [(Tj − Ta) / *Q]* − (Θjc +Θcs)

Θsa = [(125C – 65C) / 7W] − (2.5C/W + 0.31C/W)

Θsa = 5.76°C/W

A heat sink will be required with a Thermal Resistance of less than or equal to 5.76°C/W.

Extrusion Data:



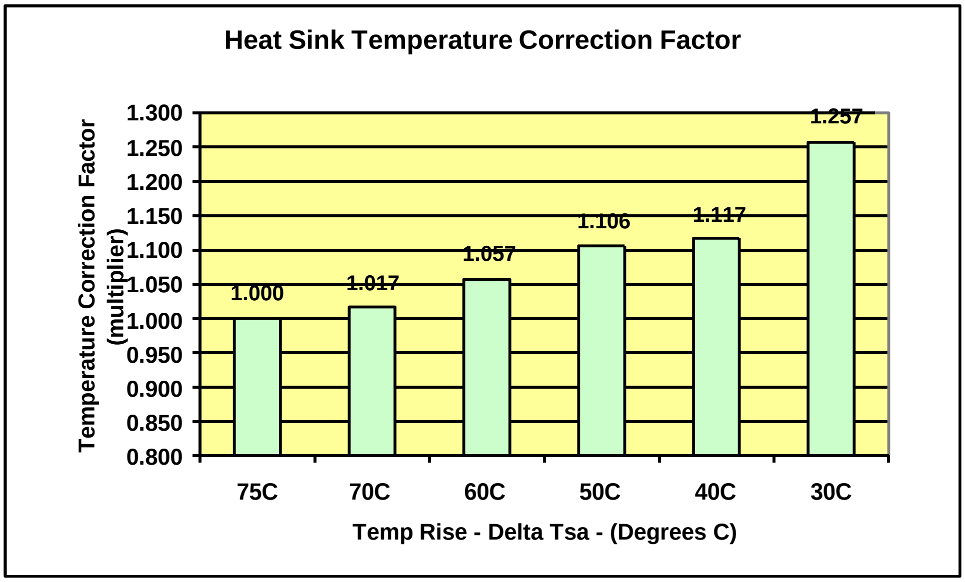
Published Thermal Performance Data

- Natural Convection = Air Flow is estimated at ~57 LFM
- Vertical Orientatio
- 3 inch long piece
- Uniform Heat Load – heat source area is entire base of heat sink

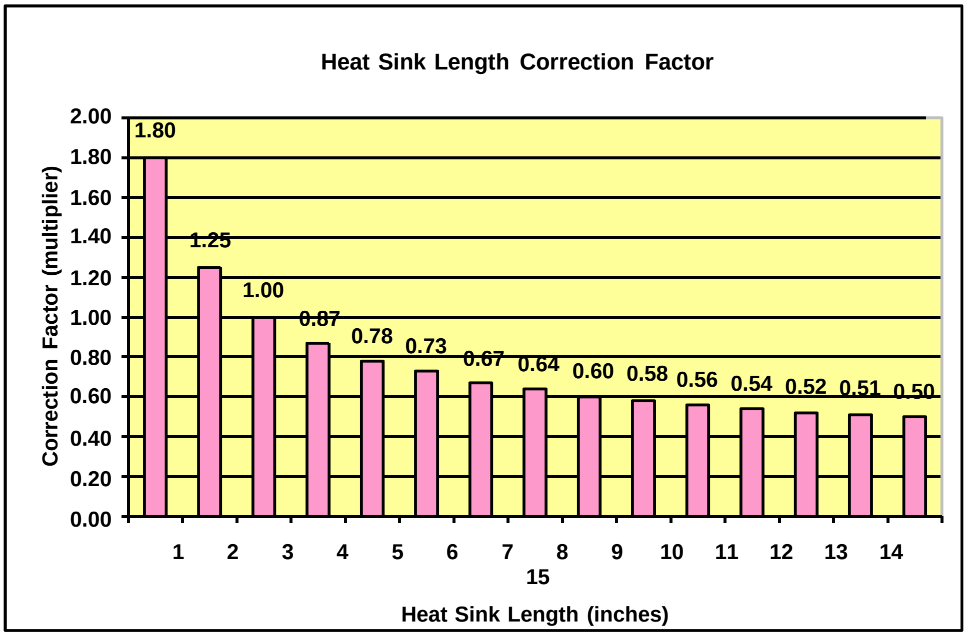
Heat Sink Temperature & Length Correction Factors:

As ΔT Decreases, the Heat Sink Efficiency Decreases …

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



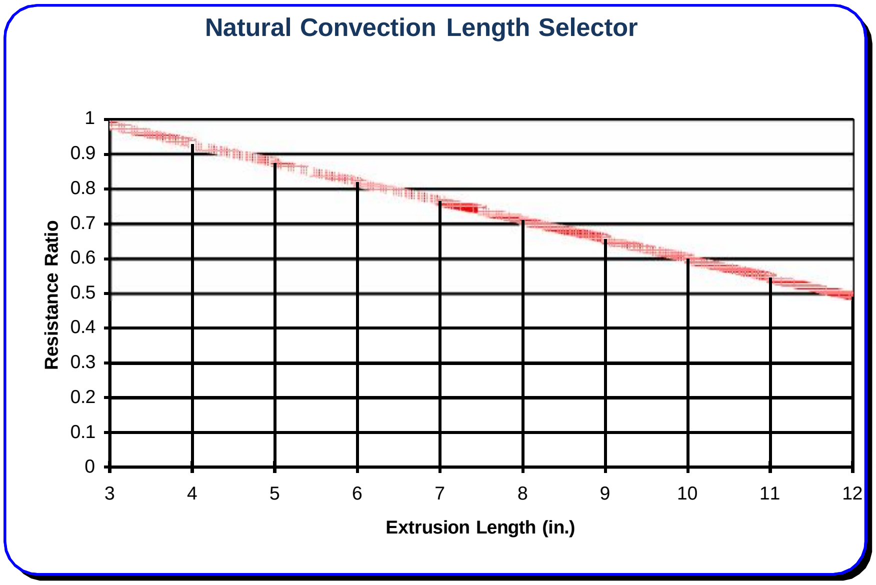
(Length Correction) x (Published °C/W/3in) = Correct (°C/W)



Selecting Extrusions Lengths for Natural Convection

Wakefield Vette provides the Thermal Resistance of heat sinks in term of 3" lengths. To select heat sinks other than 3", Wakefield Vette has also developed a size selector graph shown below. When a preferred extrusion is selected, this graph will assist in establishing the approximate length necessary to obtain a desired Thermal Resistance.

The above Graph indicates "Resistance Ratio" Verses the Extrusion Length



- **Resistance Ratio = desired θ_{sa} / θ_{sa} for 3" length (from catalog)**
- **Resistance Ratio = (-0.055 x Extrusion Length, (in)) + 1.15**
- **Extrusion Length = (Resistance Ratio – 1.15) / (-0.055)**

Suppose that we have selected the Wakefield XX2006 heat sink design (from Example 1) but now need a lower θ_{sa} value of 5.0°C/W rather than the given catalog value of 5.4°C/W/3". We have available surface area to use an extruded heat sink longer than 3" and want to find out how long the sink must be to get to the desired 5.0°C/W Thermal Resistance.

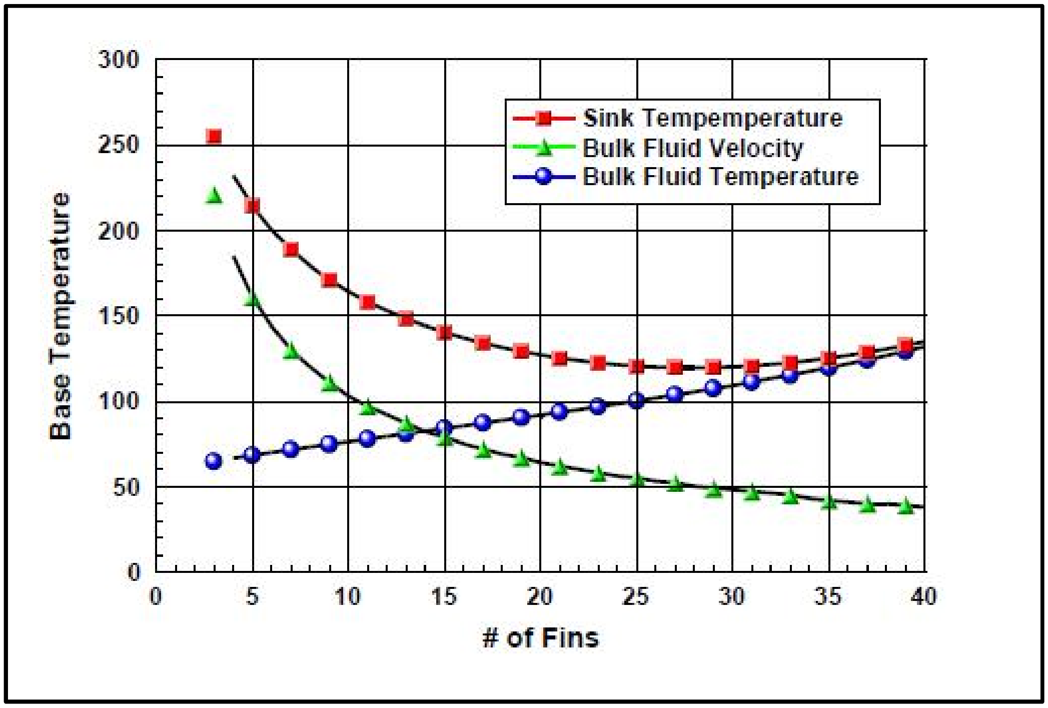
¾ **Since we have both the desired resistance and the 3" length resistance, we can use Eq. (5) to find the resistance ratio: Resistance Ratio = (5.0 / 5.4) = 0.93**

Next, we can find 0.93 on the Y-axis of the chart and follow it horizontally to the line. Reading the value on the X-axis reveals an extrusion length of approximately 4 inches. This result means that we can use a 4" or longer piece of the XX2006 to fulfill our thermal performance requirements.

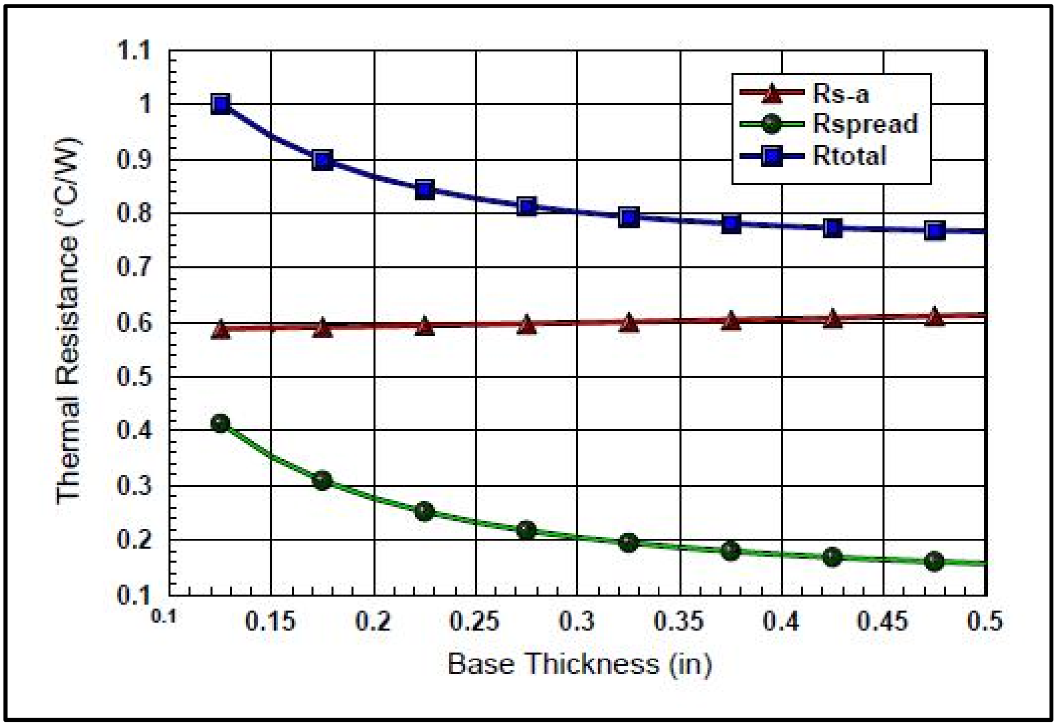
¾ **Alternatively use Eq. (7) to find the extrusion length once we know the Resistance Ratio:**

Extrusion Length = (0.93-1.15)/(-.055) = 4.0 inches

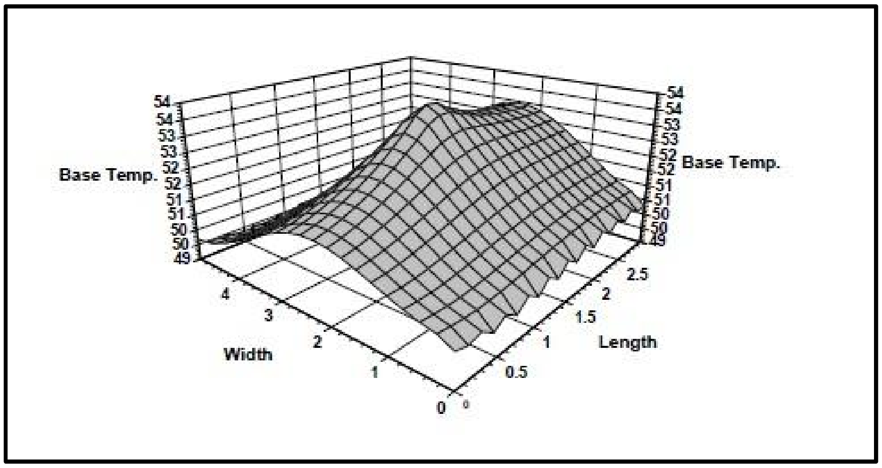
Natural Convection Analysis

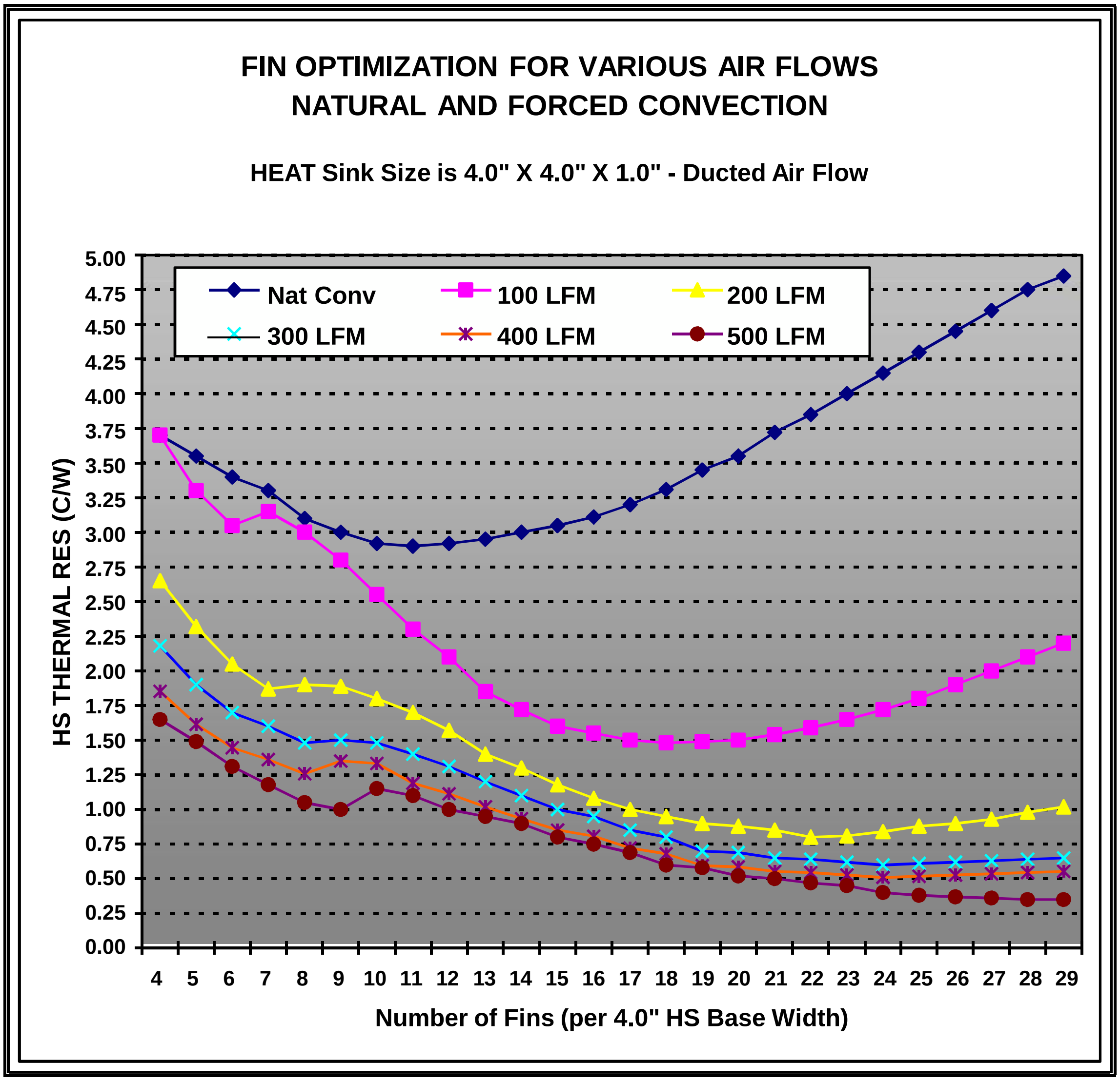


Forced Convection w/Spreading at Specific Airflow



Spreading Resistance on a Plate 15 watts - (centered on a plate)





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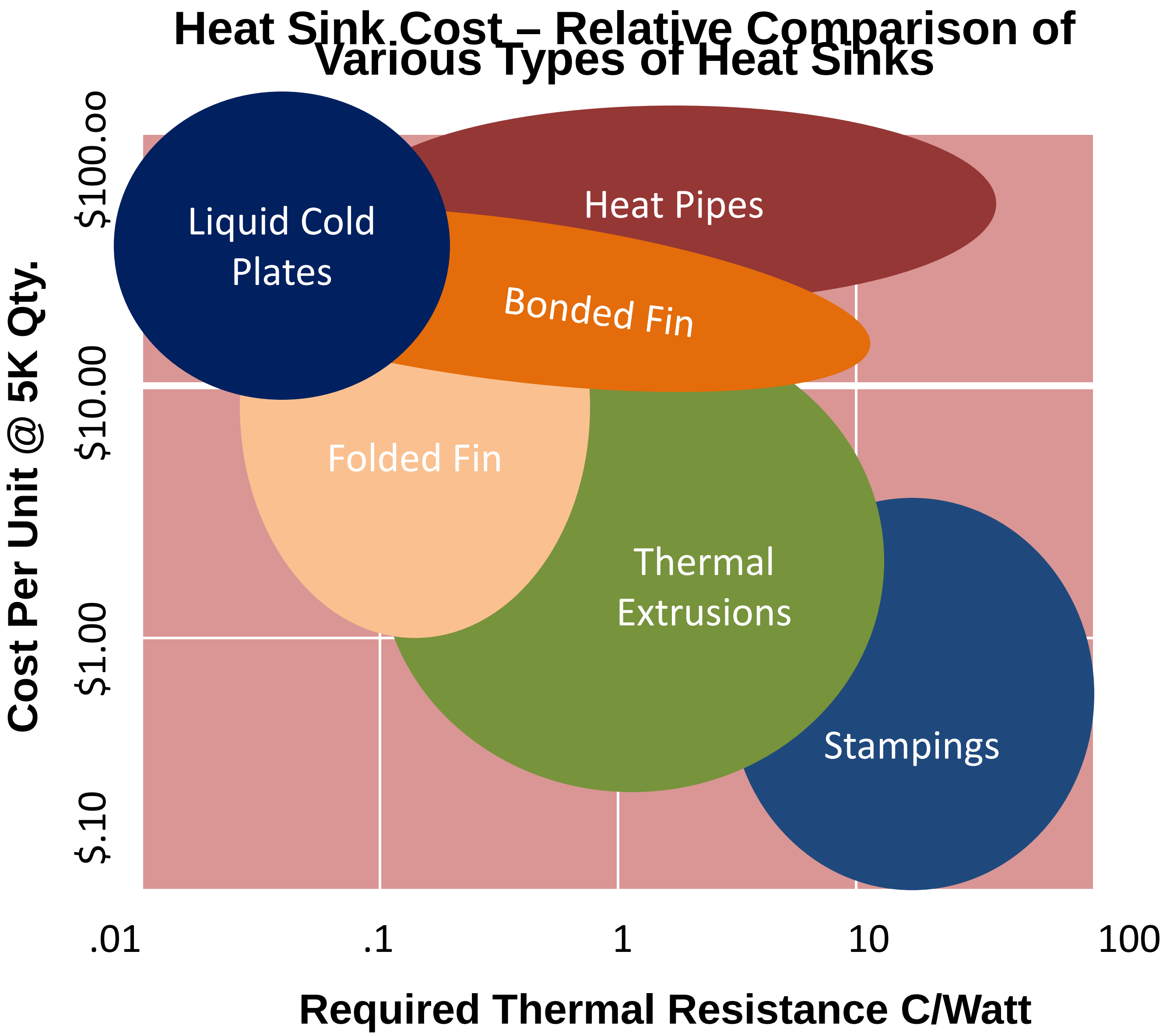

Conclusion:

Heat Sink Thermal Performance and Heat Sink Cost are directly proportional … Increased Heat Sink Thermal Performance comes at a Higher Price.

The Higher Heat Sink Price is a result of the Manufacturing Method and associated cost:

- **Stamped Heat Sinks are inexpensive and provide minimal performance**
- **Extruded Heat Sinks a moderately priced and provide mid-level performance**
- **Bond-Fin Heat Sinks are high priced and provide the better performance**