FROM THE ARCHIVES OF

ADVANCED ASSEMBLY

INDUSTRY SECRETS TO

PCB THERMAL MANAGEMENT

Four chapters of in-depth knowledge on thermodynamics, exactly how heat damages your PCB, where the heat comes from, where it goes, and the most important thermal design factors to consider.

TABLE OF CONTENTS

ADVANCED
ASSEMBLY

Chapter One:

THERMODYNAMICS REVIEW FOR PCB DESIGNERS

INTRO

If you allow the temperature of your board to fluctuate excessively, or rise to extremes, you can drastically reduce the lifespan of your design. This eBook will take a look at thermodynamic principles to keep in mind when designing your next printed circuit board.

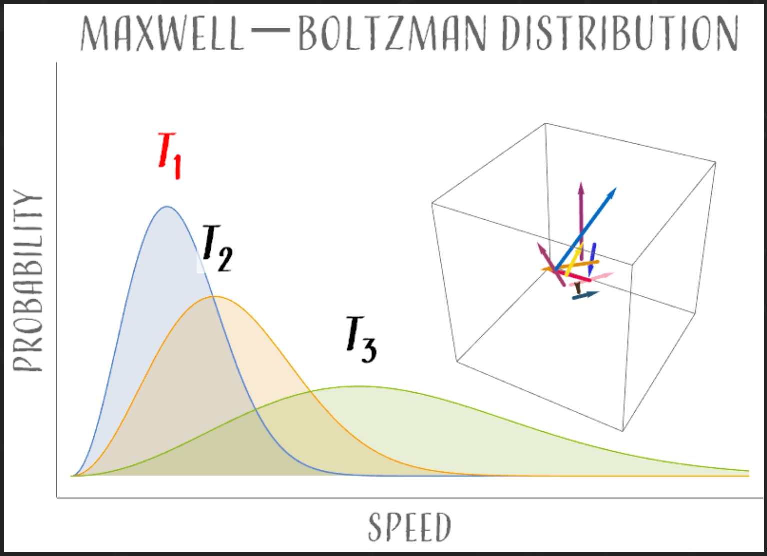
This chapter provides a quick review of thermodynamic terms. The second chapter discusses thermal failure mechanisms and basic design considerations. The third chapter discusses heat sources and heat sinks in board design. The fourth and final chapter will discuss heat mitigation tips and techniques.

If you remember thermodynamics from college, you can skip ahead to the next chapter in this eBook entitled: *How Heat Damages a Printed Circuit Board (PCB)*

A BRIEF REVIEW OF thermodynamics vocabulary

TEMPERATURE

Temperature is a property of matter that often describes the average kinetic energy of a group of atoms or molecules: their molecular mass, how fast they are moving, as well as their frequency of vibration and rotation are all taken into account. The energy of an individual atom might be higher or lower than average, but a single atom is not usually thought of as having a temperature -- it only has kinetic energy.



This animation is an artistic interpretation of the Maxwell-Boltzmann probability distribution at three different temperatures. As the temperature increases (T1<T2<T3), range of speeds of the atoms increases. The temperature measures the average kinetic energy of the entire sample.

HEAT

Heat is used to describe the transfer of energy from areas with high temperature to areas of lower temperature. Atoms with high energy collide with objects of low energy and energy transfers from the high energy to the low energy atom. These atomic collisions are similar to billiard-ball collisions: no matter the arrangement or interaction of the atoms/molecules, the atom/molecule with the greater kinetic energy transfer energy to the atom/ molecule with lower kinetic energy.

We sometimes describe matter as being “hot” or “cold.” Objects feel “hot” if, when you touch them, energy is transferred into your skin. Objects feel “cold” if, when you touch them, energy is transferred out of your skin. Heat always transfers energy from the “hot” object to the “cold” object.

The rate of energy transfer depends on the difference in temperature of the two interacting objects.

DISSIPATION

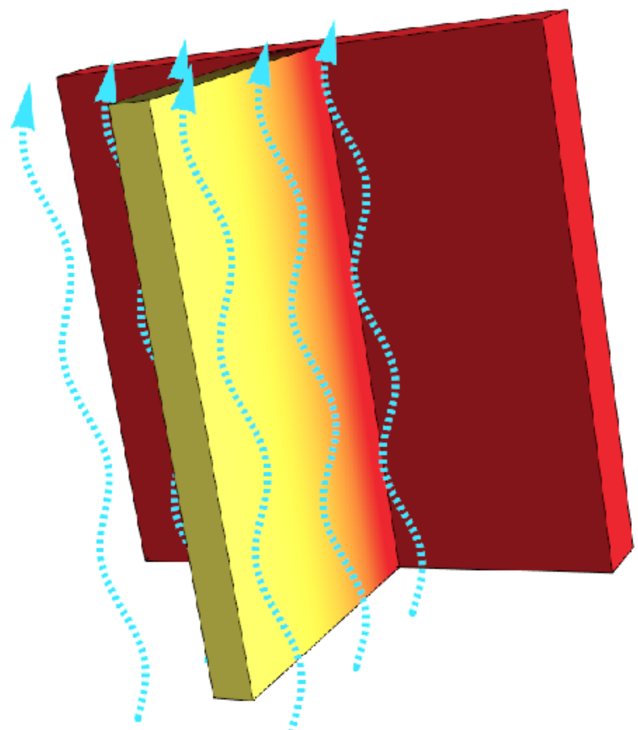
When heat is dissipated, it is transferred into the environment where it spreads out and is unable to return to the object. Unless a design intends to make use of the heat that it generates (e.g. a coffeemaker, heating pad, etc...), dissipation is usually the primary goal of electrical engineers.

CONDUCTION, CONVECTION, AND RADIATION

Heat moves from object to object through one of three commonly identified modes of transport.

CONDUCTION

Thermal energy is transferred through solid surfaces and fluids (gas and liquids) via a process called conduction. In this transfer mode, molecules stay in the same general location, but vibrate and collide with neighboring molecules to transfer energy.



CONVECTION

Vertical columns of fluid have an additional energy transfer mechanism called convection that involves the movement of atoms. In convection, energy is transferred from the high-temperature molecules of a “hot” object to neighboring low-temperature molecules of the “cold” fluid.

The extra energy in the fluids allows the atoms/molecules to collide more which increases the separation distance between the atoms/molecules. If this takes place in a pressure gradient, these excited atoms/molecules will experience larger forces in one direction than in another. That force differential allows the molecules to move away from the heat source.

You might think of this increased separation distance as causing a decrease in density. The warm, low-density fluid is constantly displaced upwards by cooler, higher-density fluid that moves down and underneath it. Once the molecules are far from the heat source, they cool, their density increases, and they sink back towards the heat source to allow the cycle to endlessly repeat.

Energy is transferred along the body of circuit-boards via conduction and is typically transferred into the environment via convection.

RADIATION

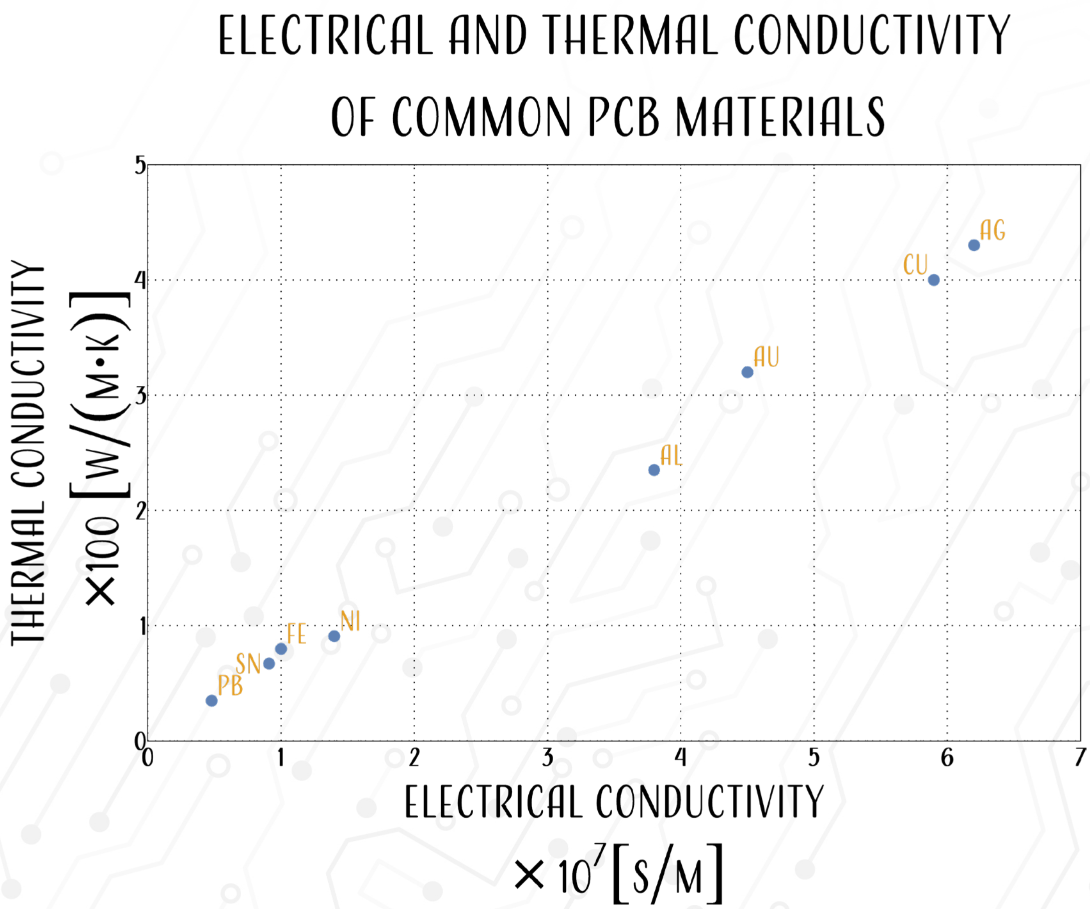
The third mode of energy transfer, “radiation”, occurs for all objects whose temperature is above absolute zero. Atoms and Molecules tend to maintain the lowest energy level possible. Anytime they have extra mass or energy, they can spontaneously emit it in a process called “radiation.” The term “radiation” is used to describe a wide range of processes and energies, not all of which are dangerous.

The collisions between molecules provide energy that allows electrons of an atom or molecule to move to higher-energy orbitals. When the electron’s fall back down to lower-energy orbitals, they emit photons -- electromagnetic waves that are usually beyond the range of human vision in the infra-red region.

Radiation is not usually a significant method of energy transfer in PCBs. However, it does allow for non-contact monitoring of the temperature of circuit boards and components using Infrared Cameras.

MATERIAL PROPERTIES OF COMMON CONDUCTORS

Some objects are better conductors of thermal energy than others, just as some objects are better conductors of electrical energy than others. Materials that make good electrical conductors (silver, copper, aluminum, etc...) also tend to be good thermal conductors; Materials that are good electrical insulators (air, epoxy, etc...) also tend to be good thermal insulators.



This graph of thermal and electrical conductivity of common PCB conductors shows a generally linear relationship between the two variables. Copper is second only to silver in its conductance. Insulators, such as the dielectric FR-4, have conductivities 7-8 orders of magnitude lower than the elements chosen for this graph and are therefore not shown.

As you can see in the graph above, Copper is around 30% more conductive than gold. So, with the increased cost of gold, and the poorer performance, why do we plate it onto our PCBs? Because copper oxidizes and corrodes over time, gold does neither. The conductance of exposed copper decreases substantially over time, while gold will perform at a consistent level at day 1 and day 1000.

SUMMARY

Chapter One provided a brief review of thermodynamic terms and definitions. Temperature is a measure of thermal energy; heat is the movement of thermal energy from one object to another. Conduction, Convection, and Radiation are ways that thermal energy can change location, and conductivity is a measure of how easily an object can transfer energy from one location to another.

Chapter Two discusses some of the thermal failure mechanisms in a printed circuit board.

ADVANCED
ASSEMBLY

Chapter Two:

HOW HEAT DAMAGES A PCB

INTRO

Nothing lasts forever, but some things last longer than others. For printed circuit boards, high-temperature environments and thermal cycling are both highly destructive conditions and all too common causes of failure in a PCB. This chapter covers a few of the failure mechanisms of components and circuit board materials.

For a review of basic thermodynamic terms, see the previous chapter in this eBook.

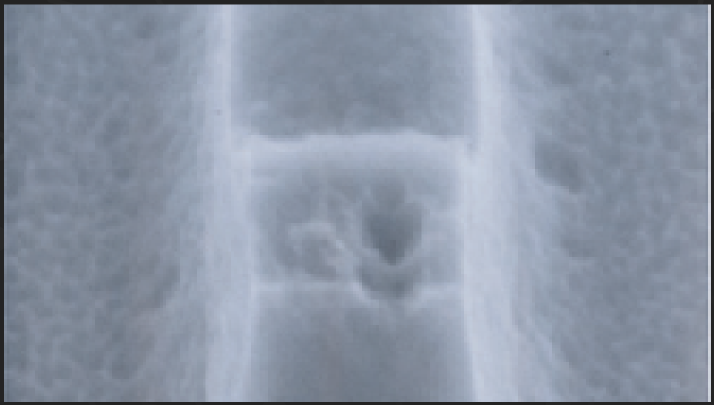
High-operating temperatures as well as other factors, can shorten the lifespan of PCBs and components and cause products to fail long before they should. Failures in a microchip die, bonding wire connections, copper pads and traces, or vias can all occur in high-temperature operating environments or when temperatures are allowed to cycle to extremes. Electrical engineers need to consider the thermal modes of their designs to ensure longevity. Below are just a few selected component-level and board-level thermal failure mechanisms for circuit boards.

COMPONENT-LEVEL failure mechanisms

Excess thermal energy can allow atoms to migrate and electrons to transition with lower applied voltages. A few of the temperature-dependent failure mechanisms in semiconductors include:

- **METAL-OXIDE-SEMICONDUCTOR** (MOS) gate oxide films breakdown and form "traps" that allow current to hop or tunnel through the film, eventually destroying the film and creating a conductive path.

- High temperatures in MOSFETs provide extra energy to allow the "**HOT-CARRIER**" phenomenon near the drain. Hot-carriers are electrons or holes that have extra thermal energy. The extra energy allows the carriers to enter the gate oxide film where they degrade the film over time. This eventually lowers the threshold voltage and transconductance of the film.

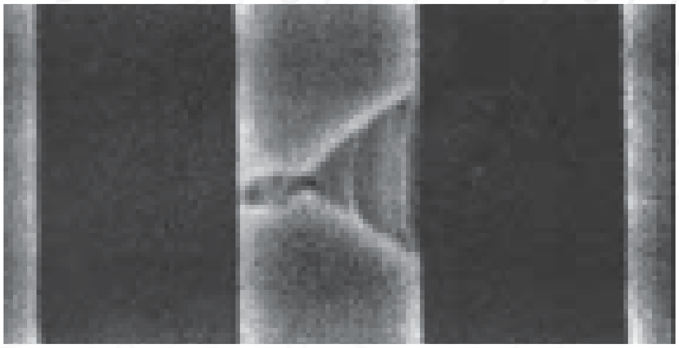


Above: This electron micrograph of a gate-pinhole is from the Renesas Semiconductor Handbook

- **ELECTROMIGRATION** allows aluminum atoms in metallized interconnection wires to move in the direction of electron flow. This can result in voids and open-circuit conditions at one end of the wire and short-circuit conditions due to a collection of aluminum at the other end. Both voltage and temperature affect this failure mechanism.

Above: Electro-migration failure from Renesas Semiconductor Handbook

- **STRESS MIGRATION** allows metal atoms to migrate due to mechanical stress in the presence of thermal energy. Tensile stress occurs due to different thermal expansion coefficients of materials, the migration can lead to voids and open-circuit conditions.



Above: Wedge-void image from Renesas Semiconductor Handbook

- Gold-plated Aluminum die-bonding wire forms an intermetallic compound called "**PURPLE PLAGUE**" at the Gold and Aluminum interface. The resistance at this junction increases over time and is accelerated by high temperatures.

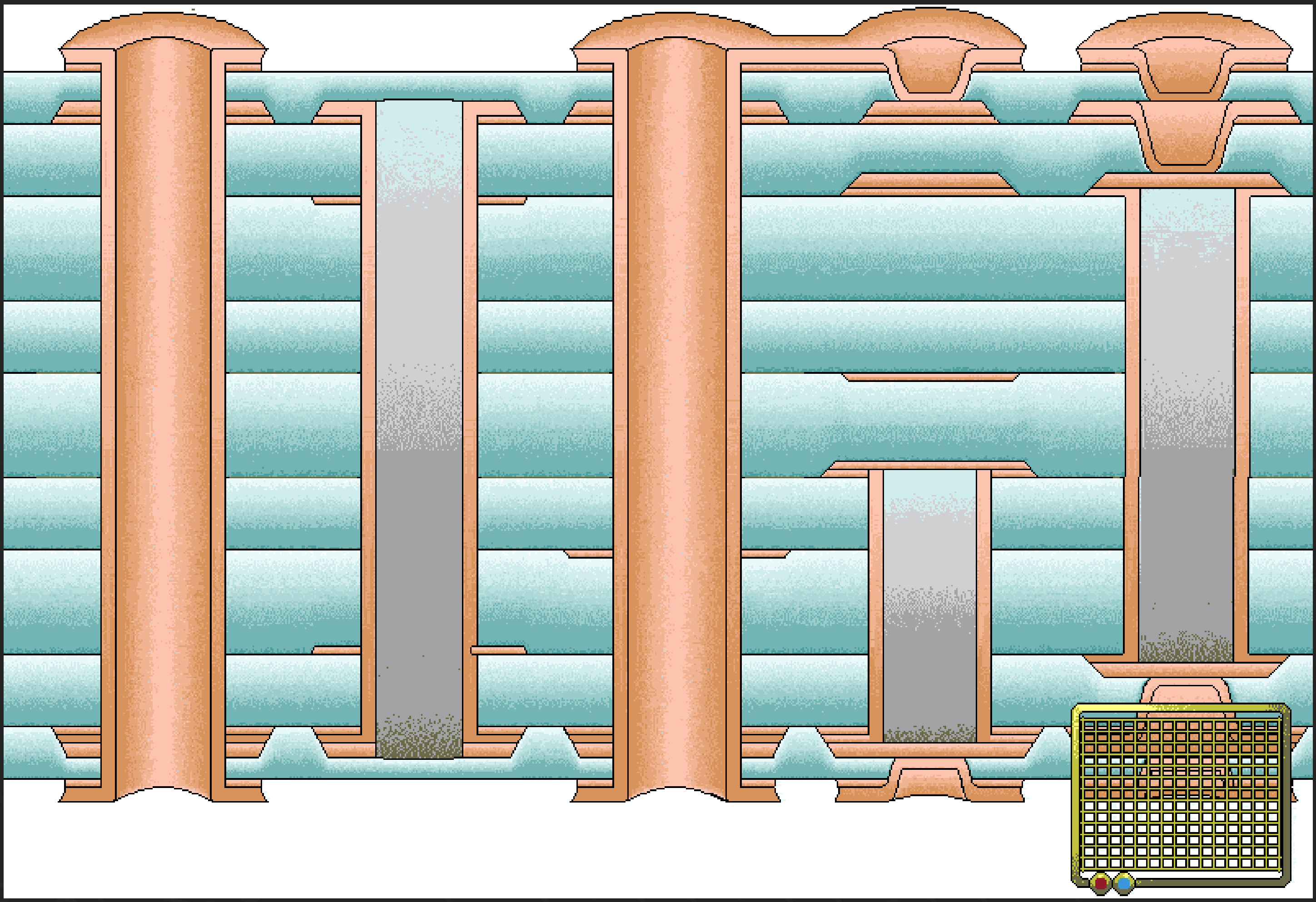
>>>

BOARD-LEVEL failure mechanisms

Excessive temperatures can be equally damaging to printed circuit boards that hold the components. Mechanical stress caused by different coefficients of thermal expansion of conductors and insulators cause via failures, board warpage, and solder bond failures.

VIA FAILURES

Copper has a much lower coefficient of thermal expansion than the fiberglass/epoxy mixture that makes up the non-conductive parts of a PCB. PCBs expand the most in the z-axis (out-of-plane) direction, and since the copper does not expand at the same rate, it puts enormous stress on the copper plating that makes the via wall as well as the copper foil that makes up each individual layer.



Above: This graphic from PWBCorp shows how the z-axis thermal expansion of PCB materials can put mechanical stress on vias. The stress can lead to barrel cracks, corner cracks, foil cracks, and more.

PCB BOARD WARPAGE

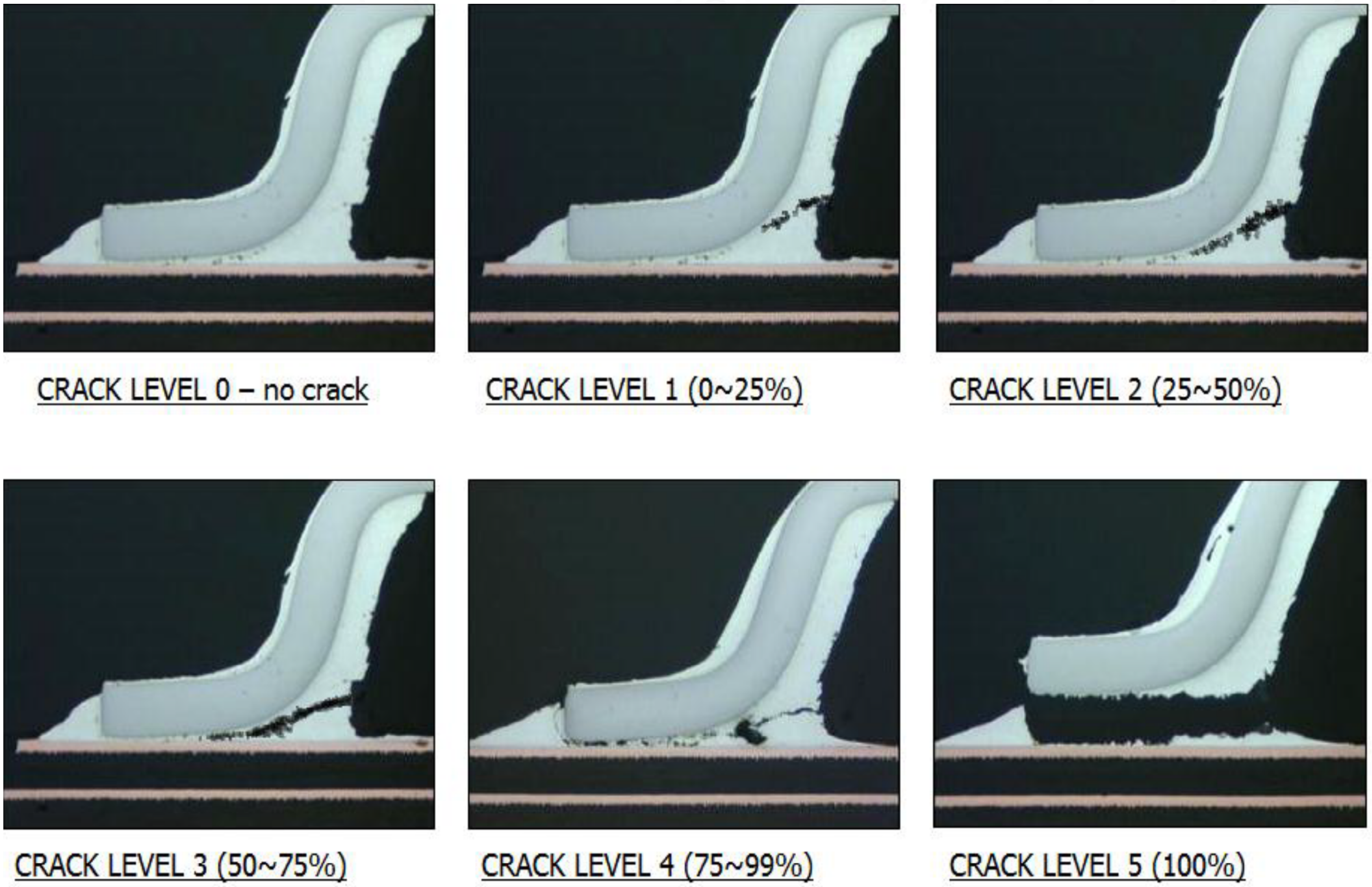
PCB board warpage is a term that is usually ascribed to the board fabrication process. When heat is applied to a PCB during lamination, the PCB layers will fully expand. Unfortunately, the coefficients of thermal expansion of copper and dielectric are very different. So an asymmetrical board stackup will cool with uneven stresses on either side of the board. The Differential tension during cooling will cause the board to warp as soon as it is removed from the press.

Whether the warpage is a twist, cup, or bow is somewhat immaterial. Without a suitably flat board surface for surface-mount-components to mate to, there can be a variety of ill-formed solder-joints that cause immediate or latent board failures.

During assembly, the board is again heated to melt the solder paste. Once the heat is removed, the board shrinks and can place stress on sensitive components such as voltage references.

CONNECTION FAILURES

As boards heat and cool during use, they expand and contract. Unfortunately, the varying coefficients of linear expansion cause the board materials and components to expand and contract at different rates and at different times. The differential expansion creates mechanical stresses that eventually lead to electrical failures.



Above: Various levels of solder failure on a component from the MDPI Materials journal article "Reliability Study of Solder Paste Alloy for the Improvement of Solder Joint at Surface Mount Fine-Pitch Components"

SUMMARY

These are just a few of the ways thermal energy can cause failure in your PCBs. The best way to keep your board in service for the longest period of time is to keep the operating temperature low and the changes in temperature moderate. Each additional degree and each thermal cycle takes your board that much closer to failure.

Chapter Three discusses where this heat comes from, and the next chapter in this eBook will discuss PCB design best practices.

ADVANCED
ASSEMBLY

Chapter Three:

WHERE DOES THE HEAT COME FROM, AND WHERE DOES IT GO?

INTRO

The *Thermal Management Techniques* eBook is focused on helping you better understand how high temperatures and large changes in temperature can lead to design failures.

Chapter Three discusses some of the sources of heat as well as some ways to dissipate it.

HOW IS THERMAL ENERGY PRODUCED?

PN-junctions, resistors, integrated circuits, traces, and other circuit components produce heat, and that heat raises the temperature of the PCB. High temperatures will shorten the lifespan of an integrated circuit, and temperature fluctuations will lead to mechanical failures, so it is important to take steps to limit heat generation, and constantly dissipate the unavoidably generated heat into the environment. Keep the temperature of the device as close to the ideal operating temperature as possible, or more realistically, keep the temperature changes within design limits.

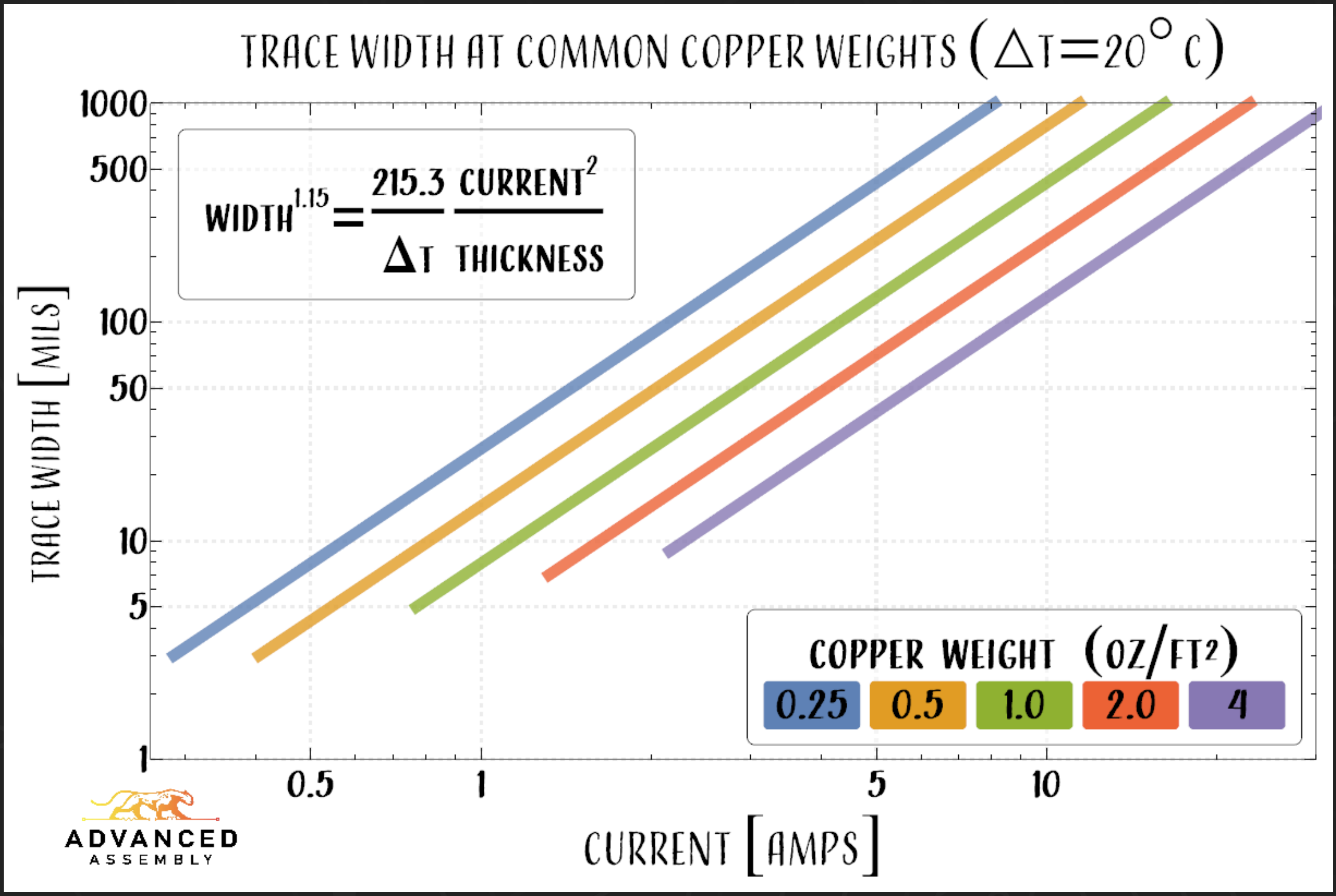
Ohmic-devices (resistors, conductors, heating elements, etc...) have a simple direct proportional relationship between potential difference and current. The power dissipated in these devices can be easily calculated. Non ohmic-devices (Integrated circuits, light-emitting diodes, MOSFETs, PN junctions, etc...) have a more complex relationship between V and I -- so datasheets must be read, and graphs must be interpreted to determine the power dissipation.

CURRENT-CARRYING CAPACITY OF A COPPER TRACE

One often overlooked source of heat generation (and dissipation) in PCBs is high-current ohmic heating in traces. Copper, while still an excellent conductor, still presents some resistance to electron flow. The heat generated within a trace is determined with $P=I^2R$, while the heat dissipated by the trace has a more complicated relationship with the environment and underlying PCB -- the heat dissipation is determined empirically.

The book “PCB Trace and Via Currents and Temperatures: The Complete Analysis 2nd Edition” by Dr. Douglas Brooks looked at the relationship between copper trace thickness, track width, current, and temperature. Use the equations provided at his website Ultracad.com to calculate an appropriate copper weight and thickness for your design. The general idea is to use a trace that is thick enough and wide enough to prevent excessive heating of your circuit board and components.

I selected a 20°C maximum temperature increase and calculated the minimum trace width required to carry a given current at a variety of trace-widths. The graph is shown below.



This graph rearranges Dr. Brook's mathematical model to determine the trace width for a variety of copper weights and current requirements using ΔT=20°C as the limiting factor. As an example, 5 amps of current can be carried by a 200 mil, 0.5 oz copper surface trace, or a 40 mil, 4 oz copper surface trace.

Chapter Two listed a variety of failure mechanisms for components and PCB boards. This chapter showed various sources of heat in your design. Now it's time to discuss a variety of ways in which you can dissipate heat in your designs.

If your board, or any component on it is going to be installed in an environment where the ambient temperature is above ~40°C, or the change in board or components exceeds 20° C above room temperature, you should at least consider some of the ways in which you can dissipate heat in your design.

HEAT SINKS

Heat "sinks" absorb heat via conduction and dissipate heat via convection.

These devices are very effective at dissipating energy into the environment which keeps their temperature low compared to the high-temperature part that they are attached to. The IC is the heat "source" and the aluminum or copper part is the heat "sink".

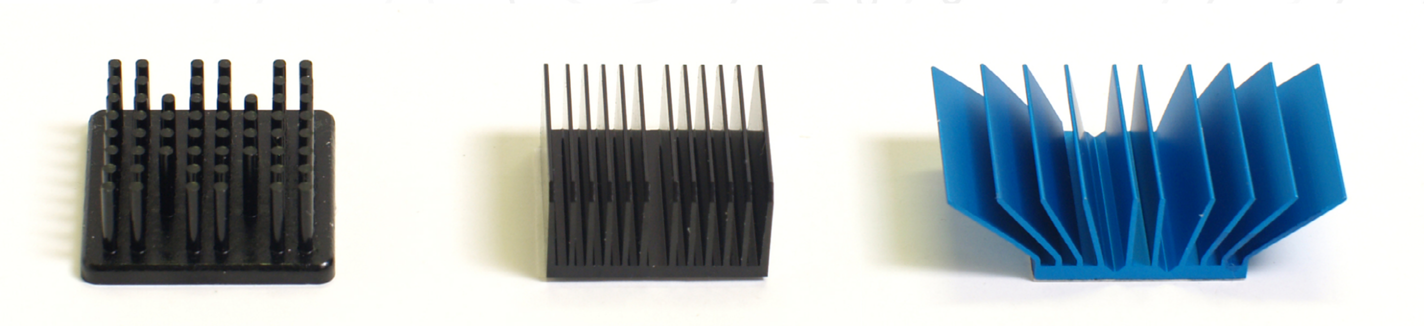
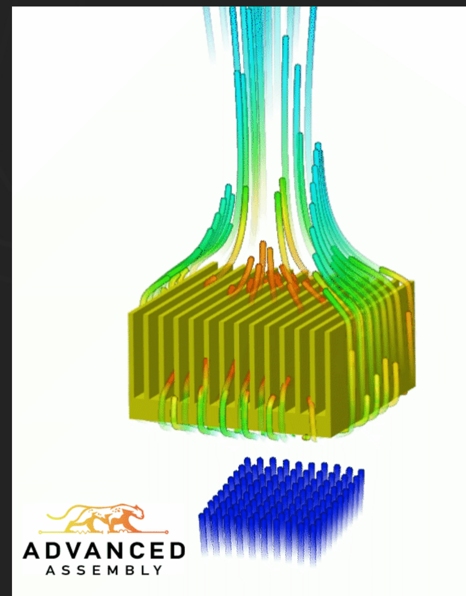


Image of straight-pin, straight-fin, and flared-fin passive heat sinks from Wikipedia.com

STRAIGHT-FIN HEAT SINK

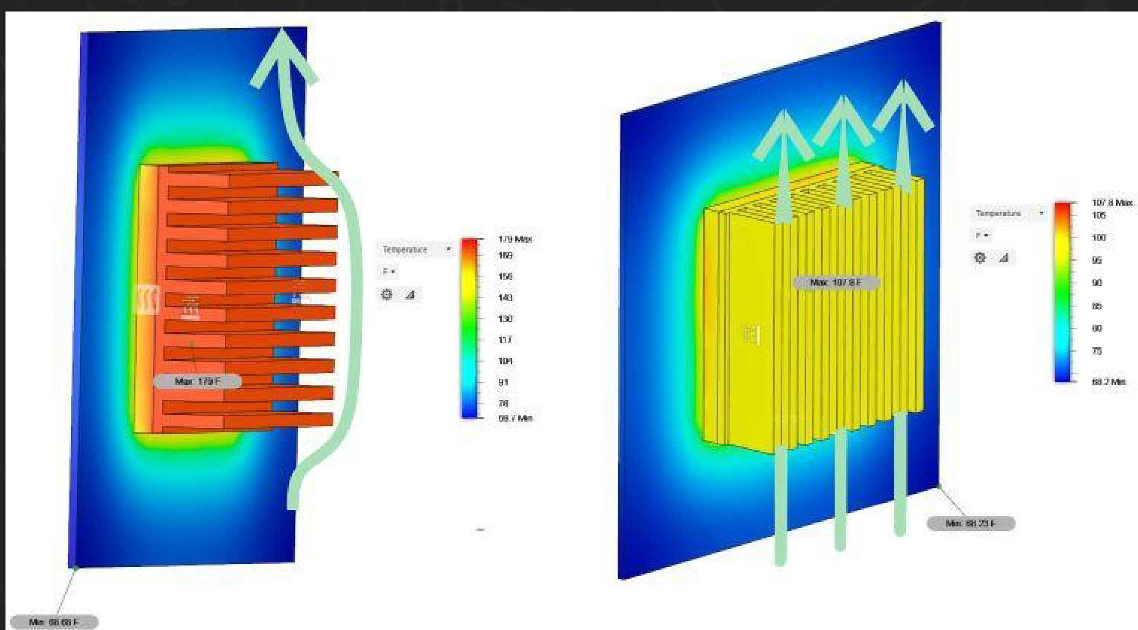
Straight-Fin heat sinks can be added atop your IC to aid in heat dissipation. There can be no gaps between the heat-sink and the IC because any separation will capture air and prevent heat from moving from the IC to the heatsink. Use thermal grease or another heat-sink compound to thermally connect the two objects.

Straight-Fin Heatsinks depend on either passive convection or active forced airflow. If you are using convection to cool your component, it is important to think about the direction that the board will be oriented in your project. The best orientation, shown in the animation to the right is with the long edges of the fins pointing up.



This animation uses computational fluid-dynamics to illustrate the movement of air around a theoretical heat sink. Cool air is drawn in from the bottom and sides where the fins transfer heat to it. The hot air rises and moves away, allowing more cool air to be drawn in.

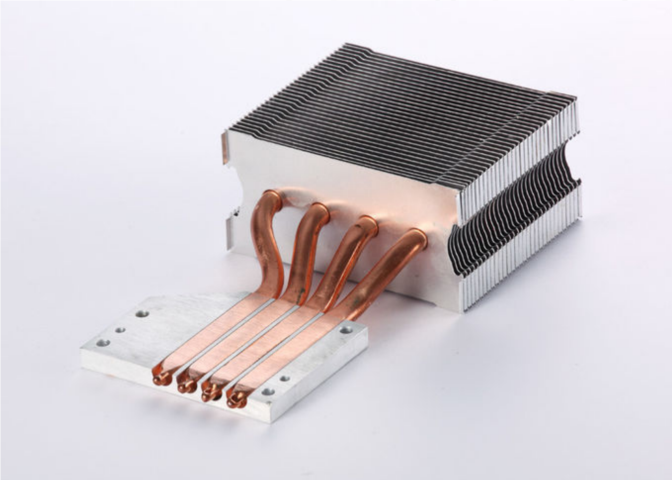
The second-best orientation is with the short edges of the cooling fins pointing straight up, as this still allows air to flow through the fins of the heat-sink. The worst orientation is with the long sides of the cooling fins oriented vertically, as air cannot move easily in and through the heatsink.



This fictional heat sink's performance was evaluated with Autodesk Fusion 360. On the left, the long edges of the fins are horizontal. In this configuration, air cannot easily move between the several fins, and the temperature of the heat sink is over 80° F than when the long edges of the fins are positioned vertically, shown on the right.

If you are creating something that is bound to be hot and must be kept cool -- you can even add heat pipes or heat exchangers to your design.

This Copper Heat-Pipe and Aluminum-Fin heatsink from Lifong Industrial in Hong-Kong shows how Aluminum and Copper can be combined to maximize performance and cost-efficiency by mixing materials. Even though it is somewhat less conductive, Aluminum is often used for heat-sink fins because it is less expensive than copper.



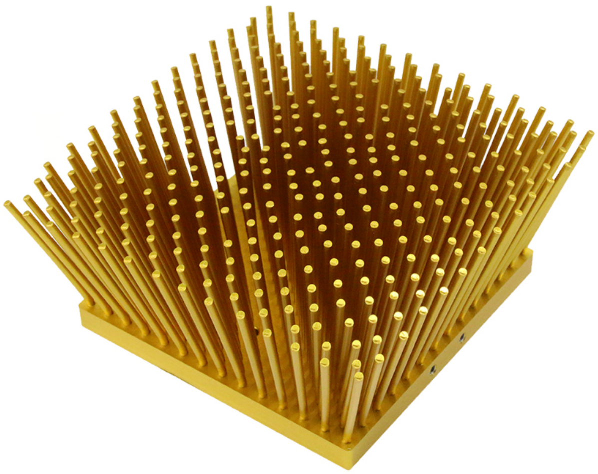
If you are actively pushing air through the fins with an electric fan, the orientation is not as important as the volume flow rate. Remember that once in service, the fins will eventually be covered with dust or debris and they will not cool the device as well as expected. You should derate your design based on the environmental conditions at the installation site. Your design should incorporate on-board thermocouples that can signal your board to shut down if the temperature of the board rises too high.

FLARED-PIN HEAT SINK

Higher-performance heat sinks are available, such as the flared-fin and flared-pin heat-sinks. While it does offer greater heat-dissipation capabilities, it comes at increased manufacturing cost. Flared-fin heatsinks must be extruded to be affordable in large quantities.

PIN-FIN HEAT SINK

If you do not know what orientation your heatsink will be in the final installation, consider a pin-fin heat-sink. These heat-sinks perform well in almost any orientation.

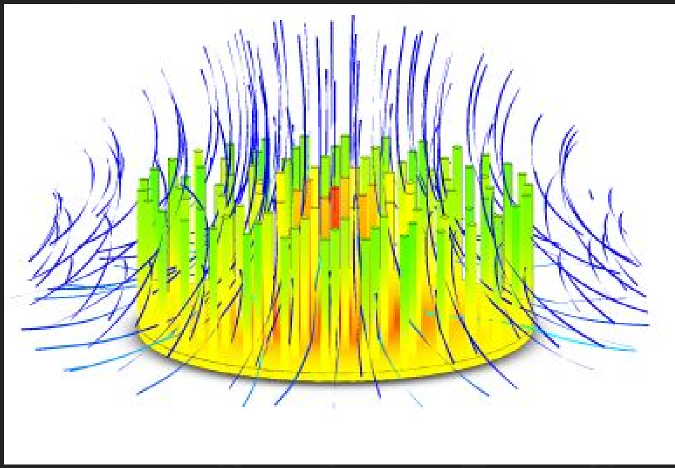


This pin-fin heatsink from Renxin thermal technology can be installed in any orientation -- with either the x-axis, y-axis, or z-axis pointing vertically and still allow passive heat dissipation via convection.

The goto-solution to analyze a heatsink's performance is with a multi-physics simulation program that can handle computational fluid dynamics (CFD) for convection in fluids, as well as finite element analysis (FEA) for conduction in solids.

If you make a Detailed Thermal Model (DTM), you can very accurately predict the temperature at all points in your system, at the expense of a significant time investment setting up and then running the model. A Compact Thermal Model looks at heat at several key points in a design and can be set up and computer in less time than a DTM.

If you'd like to experiment, SimScale is a free online multiphysics simulator that allows users to model airflow around a PCB. The following simulation shows heat flow around a free-floating heat-sink.



CFD visualization of a straight-pin heat sink from Wikipedia.com

SUMMARY

When designing for thermal dissipation you can either estimate or simulate. In either case you should have a good understanding of the heat sources in your design so that you can decide how best to dissipate heat from your design. In any case, be certain to suitably derate your calculations to account for uncertainty errors as well as unforeseen circumstances.

ADVANCED ASSEMBLY

Chapter Four:

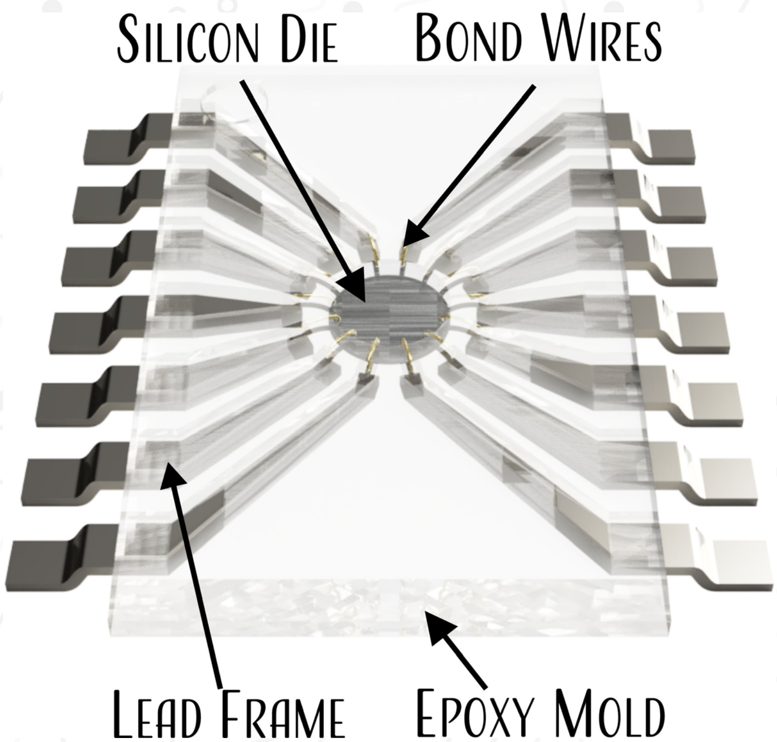
THERMAL DESIGN DECISIONS & CONSIDERATIONS

MAKING THERMAL DESIGN DECISIONS FOR YOUR PCB

Deciding how to arrange the components of your board, which heat sink to purchase, and even what clock-speed to run a microcontroller all require that you have a thorough understanding of your part construction as well as a decent idea of how to estimate or calculate the rates of heat transfer for conduction, convection, and radiation.

THERMAL CONDUCTIVITY OF PCB MATERIALS

PCBs are made of sandwiched layers of copper and dielectric. ICs are made of epoxy, silicon dies, bonding wires, and a metal leadframe.



This artistic impression of a 14-pin small-outline package shows the basic parts of an IC entombed in its epoxy mold.

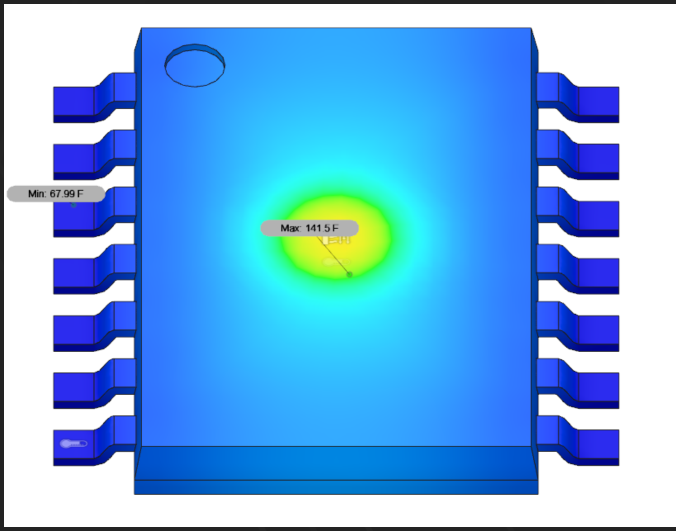
The silicon dies inside a package and copper on a PCB are both excellent conductors of heat, solder is a decent conductor, and the PCB dielectric and Epoxy mold are very poor conductors of heat.

Material	Approximate Thermal Conductivity $\left(\frac{W}{m \cdot K}\right)$
Silicon	150
Copper	390
Dielectric (FR4)	0.4
Solder	50
Aluminum	240
Epoxy Mold	0.15-0.25

Approximate thermal conductivity of selected common PCB materials.

The die is usually centrally located in the epoxy package, and the same die can be used in several package sizes. While the gold/aluminum bonding wires are decent thermal conductors, they have a very small cross-sectional area, and aren't good at transferring heat from the die to the pins.

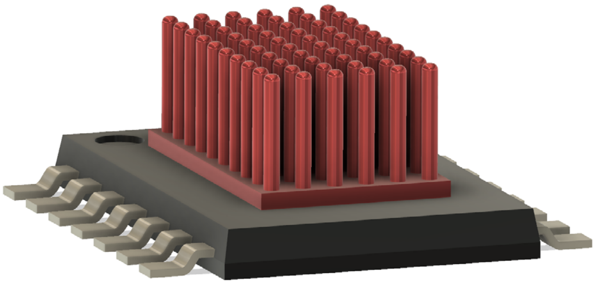
That means that the heat generated in the die has a hard time moving throughout the epoxy packaging. Any substantial heat movement will take place near the die, which is usually located near the very top of the epoxy mold.



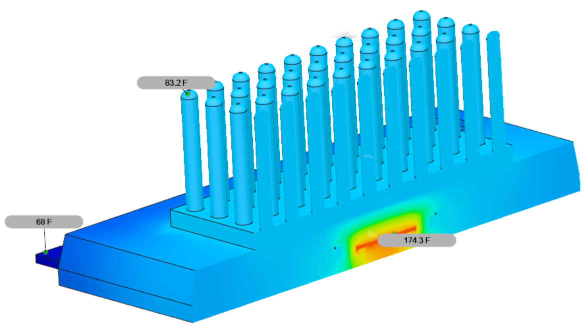
This thermal simulation of the fictional IC shown above demonstrates that the heat generated by the die does not spread out over the entire surface of the IC. The epoxy body limits the heat transfer. An actual IC would spread heat over a greater area because IC dies are usually larger than the one shown in the artistic image at the beginning of this chapter.

Where your die is in your package dictates the direction of heat flow in your design. Packages that do not have thermal ground pads dissipate their heat upwards. For those packages, you are usually forced to use a heat-sink to dissipate excess thermal energy.

Packages with thermal grounds and flip-chip packages usually encourage the designer to move the heat down into the PCB via conduction, into the ground plane, and dissipate it somewhere else on the PCB.



A straight-pin heat sink attached atop the device does an excellent job dissipating heat if convection is present.



This cutaway image shows the thermal analysis of this fictional IC and straight-pin aluminum heat-sink shows that the pins as well body of the IC stay within 20°C of ambient temperature with the straight-pin heat-sink dissipating almost 100° F into the environment. A real IC would have the die closer to the top or bottom of the package, not centered in the middle.

HOW TO CALCULATE THE COOLING CAPACITY OF A HEAT SINK

YOU HAVE TWO OPTIONS:
CALCULATE OR SIMULATE

Heat sinks dissipate energy via convection and radiation. The equations that describe their dissipative power are more tedious to implement than they are difficult. A typical electrical engineer with a simple design and a half-day to study examples might apply the pertinent equations to their design with sufficient accuracy to avoid the need of further investigation.

If your design requires anything more complicated than putting a heat-sink on top of a microcontroller, you should either simulate your board, or consult a thermal engineer. Not only do thermal engineers have experience with simulations, which means they can get results faster than you can, but their real-world experience can be invaluable to designers. They know how to derate results as well as how to save on production costs of a final design. A thermal simulation or consultation with a thermal engineer is equivalent to an increase of 40 IQ points, especially at the beginning of your career.

RADIATION

Radiation is governed by the Stefan-Boltzmann equation, which requires basic algebra to implement for simple shapes. Radiation becomes increasingly useful mode of heat transfer in high-temperature designs.

CONVECTION

Convection is the more difficult calculation to implement as the equations become a bit more involved. If the heat-sink or other device is rotated in space, depends on a fan, or might be used in a variety of environmental conditions, you need to figure out how to derate your design. Many an engineer has found that their design works well on their test bench, but not so well in a house in Denver, Colorado where the pressure is nominally 17% less than the pressure at sea-level. Even MIT engineers have made this mistake while designing receivers for their high-altitude Radio-telescopes. At 9200 ft, the atmospheric pressure is 30% less than at sea-level.

CONDUCTION

Conduction is perhaps the easiest equation to implement. The math isn't too difficult, but what does stump the average EE is how they combine the results from their radiation and convection calculations with their conduction calculations. Conduction moves heat into and around the board, but without radiation and convection, it will simply accumulate on the board, raising the overall temperature of the design.

SIMULATION

Finite Element Analysis breaks your design into a collection of individual miniature cells that each start out at a particular temperature. Each cell can also has additional mechanical properties assigned to it, such as thermal conductivity, coefficient of expansion, etc… Then, with each increment of time, the computer looks at the current temperature of each cell, and all the cells that border it, and calculates the new temperature. This can be a time-consuming task for a single computer, but parallelization "in the cloud" can bring the computation time down from days/weeks to minutes/hours.

There are a growing number of simulators on the market. If your toolchain provides thermal analysis (Solidworks, Autodesk, etc…), you might already have thermal simulations available to you. If you do not, you can purchase a license or find free software online such as SimScale. If you plan on making a large order of heat-sinks or heat-exchangers, you might be able to convince the factory you order your board from to provide a detailed thermal analysis of your design as part of the contract.

Usually, heat is moved around a board using conduction and away from a board using convection and radiation. To determine the final operating conditions of your board before it is manufactured, you can obtain a decent estimate for simple designs through calculation, and an excellent estimate through computer simulation.

THERMAL DESIGN CONSIDERATIONS

Vias move thermal energy up and down between the layers of a PCB. Large cross-sectional areas of copper move the heat along the length and width of the board. So how do you consciously incorporate thermal design into your next board?

The first design consideration is to limit heat production on your board, the second consideration is to move it away from sensitive components, and the final consideration is to move it off of your board.

REDUCE THE AMOUNT OF THERMAL ENERGY GENERATED BY YOUR DESIGN

COMPONENT SELECTION

Thermal energy production is a consequence of material inefficiencies. So step one is to use better components made of more efficient materials if they are available to you.

SiC and GaN

If you are a power engineer, you've likely created designs that use Silicon MOSFETs -- they have been in the industry for decades. And for the last ten years, we have been promised Silicon Carbide (SiC) MOSFETs and Gallium Nitride (GaN) MOSFETs. While we continue to wait for GaN to reach widespread presence on the market, SiC MOSFETs are already available from several manufacturers and have proven reliability statistics (Rohm, Wolfspeed, etc...).

Compared to their predecessors, SiC MOSFETs are an order of magnitude thinner and have three orders-of-magnitude lower on-state resistance. That 10^3 reduction in resistance means 103 reduction in power dissipation, which, of course means a 103 reduction in heating. So depending on your design, you can go from forced-air-cooling to passive-convection, or from a large external heat sink, to no heat sink at all.

CONTROL YOUR VOLTAGE AND DUTY-CYCLE

Every PN junction in your design will dissipate heat during operation. The amount of heat generated by your design is dependent on the unused electrical energy in your design.

If you are running a high-output LED, decide whether or not it really needs to be on full-power output mode 100% of the time. A physiological phenomenon called "Persistence-of-Vision" describes a physical limitation in the cells in our eyes that causes light to seem present for longer than it actually is. An LED display that uses 2000 Hz scrambled pulse-width modulation will appear flicker-free to both humans and video cameras. If it has a 75% duty cycle, it will only produce 75% as much heat compared to if it were on full time.

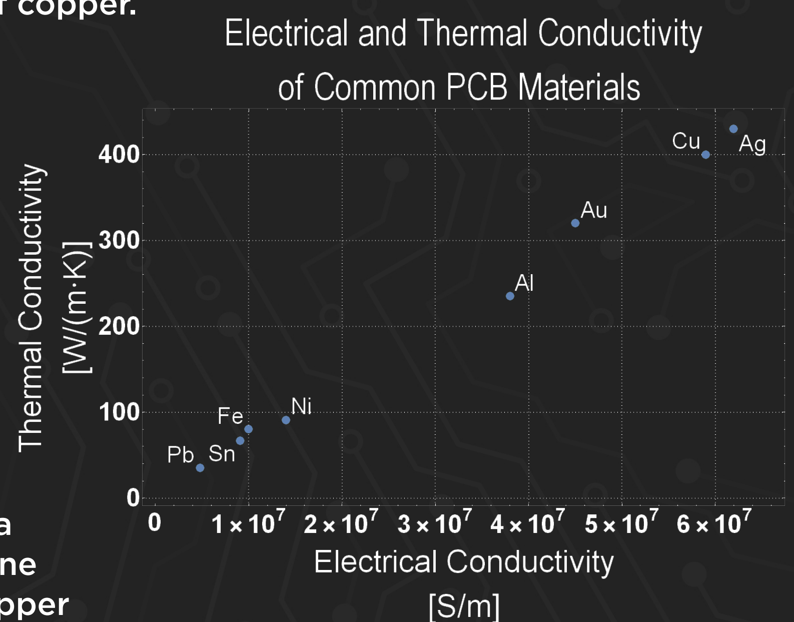
A common microcontroller and CPU option of "overclocking" uses faster clock rates to increase the speed of computation. Unfortunately, the capacitance inherent in all designs tends to limit the rise-time to reach the logic-high-threshold, which means that logic states might be indeterminant at these higher frequencies. To get around this limitation, designers increase the operating voltage of the IC -- higher voltages decrease the rise-time and ensure proper function. Unfortunately the extra electrical energy is converted into extra thermal energy during operation, which leads to higher temperatures.

So, can you take advantage of your microcontrollers ability to run at multiple operating frequencies? Perhaps you can operate at 32 kHz in a sleep / low-energy mode and then switch to 25 MHz operating frequency when the device wakes up. The more time spent in sleep, the less thermal energy you will generate.

MOVE HEAT AWAY FROM YOUR SENSITIVE COMPONENTS

Thermal conductivity measures the ability of a material to transfer thermal energy from high-temperature areas to low-temperature areas. Of materials commonly found on a PCB, copper is second only to silver in its electrical and thermal conductivity. If your IC is runs at a high temperature, you need to find a spot on your circuit board that you can maintain at a lower temperature, and then connect the two locations with an ample number of vias and copious amounts of copper.

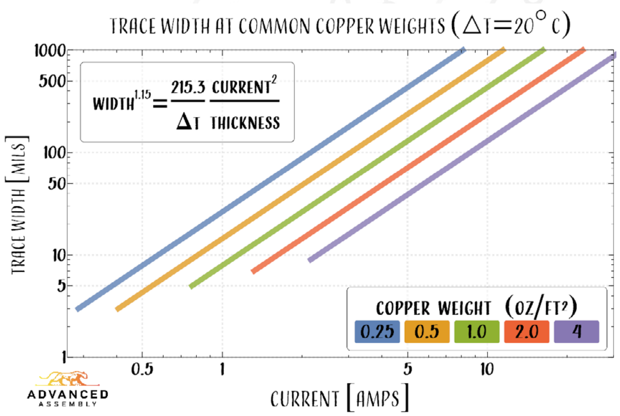
This graph shows the thermal and electrical conductivity of several metals commonly found on PCBs. Dielectric materials are not shown on this chart since they would all overlap in the lower-left corner of the graph.



Copper (~400 W/(m·K)) is two-three orders of magnitude a better thermal conductor than air (~0.2 W/(m·K)) and the common dielectric material FR-4 (~0.4-1 W/(m·K)). So, if you have a component that is generating heat in one area of the board, you can use wide copper traces and copper pours to direct the heat energy to another location on your board. If you spread the heat over a large area, it will more quickly dissipate into the environment.

But what if your copper trace is the source of the heat? High current traces are susceptible to ohmic-heating through $P=I^2R$. You can probably guess that trying to push 100 A of current through a 26-awg wire will quickly result in melting of a wire. But where is the sweet-spot? How do you calculate the ampacity of circuit board traces for a given operating temperature? Fortunately a group of engineers empirically measured the heating of a trace for a variety of thicknesses and currents and combined the results in IPC-2152. Equations were then fit to the curves by Drs. Douglas Brooks and Johannes Adams. (Visit https://www.ultracad.com/articles/pcbtempr.pdf to learn more).

For example, if you decided that you wanted your traces to heat no more than 20° C, you could use the following graph to select the right combination of copper weight and trace-width for your exterior layers. Along each of the plot-lines, the heat-generation is equal to the heat-dissipation into the environment. Interior layers do not use 215.3 in their calculations. See Dr. Brooks book (https://www.ultracad.com/thermal_book/thermalbook.htm) or IPC-2152 for more information.



This graph shows the relationship between exterior trace-width and current for a variety of common copper thicknesses. The graph assumes the designer allows up to 20° C heating of the traces.

USE A NEW DIELECTRIC MATERIAL

FR4 is a common material, but it is far from the only material on the market. There are several companies that provide dozens of dielectric materials with different thermal properties. Rogers, Bergquist, Isolar, etc... check with your fabrication company to find a material that will work for you. A dielectric with a thermal conductivity of ~4-5 W/(m·K) might be sufficiently conductive that you no longer have to embed a copper plane in your stackup.

MOVING HEAT OFF OF YOUR BOARD

Most designers are able to use passive techniques to cool their boards. If you are not quite so lucky, you will have to incorporate heat-sinks and possibly forced-air flow. See *Chapter Three* to learn more on heat-sinks.

Over the course of this eBook, we've covered everything from the mundane definitions used by thermodynamics to how heat damages a circuit board to the more intricate details of simulation. Thermodynamics might not be everyone's favorite subject, but a better understanding of how heat moves around and out of your board will make you a better electronics engineer.

We hope you enjoyed this eBook on thermal management techniques for PCBs. If you have topic suggestions for more, please submit them to marketingdept@aapcb.com.

If you still have questions regarding thermal management, or would like more information about Advanced Assembly, visit www.aapcb.com, or contact us at (800) 838-5650.