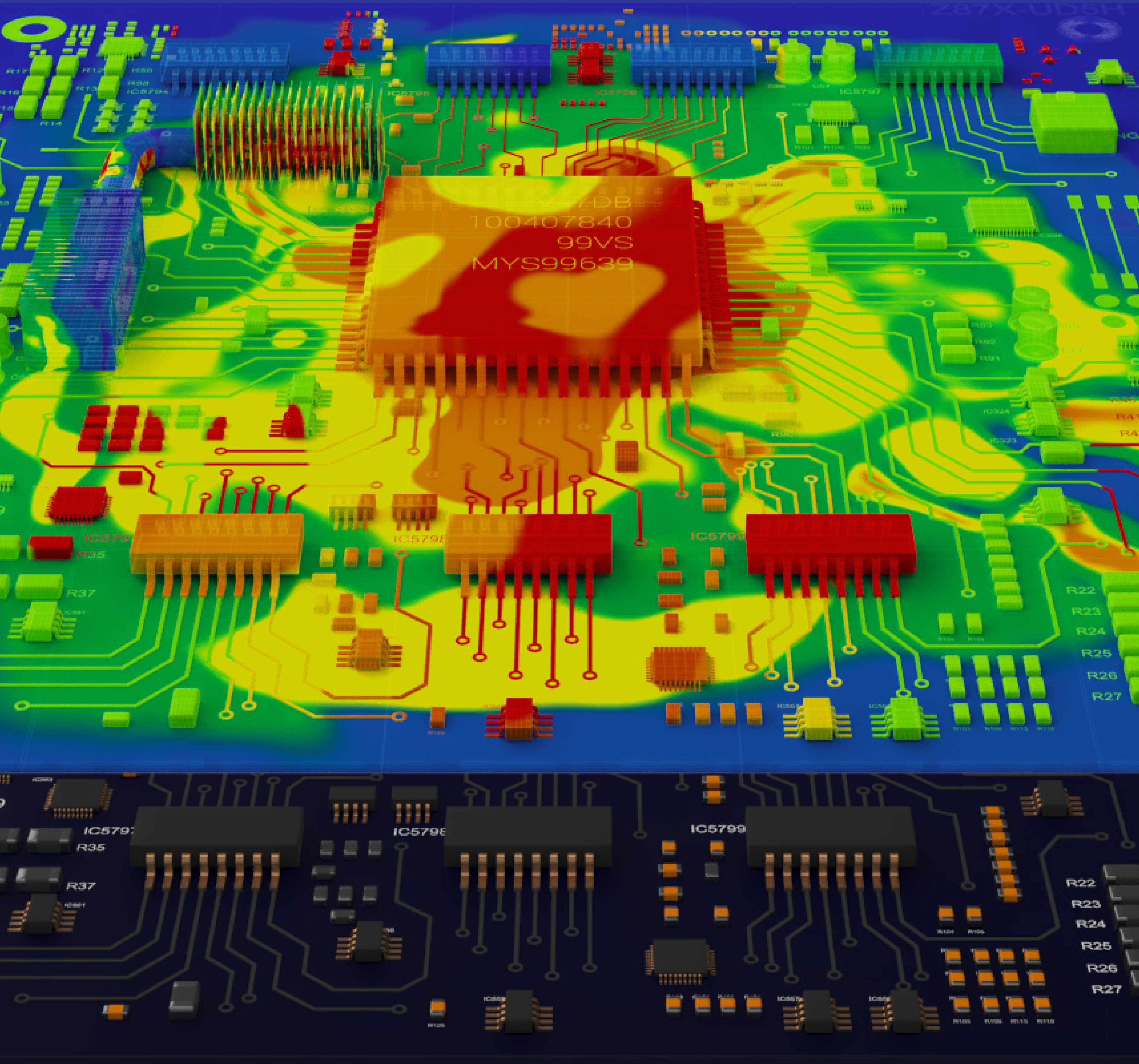


INTRODUCTION TO PCB THERMAL ANALYSIS

EMA Design Automation®

INTRODUCTION TO PCB THERMAL ANALYSIS

Thermal analysis is becoming increasingly important in PCB designs as electronics are producing more heat and thermal dissipation impacts power consumption, user experience and performance. Depending on the stage in the PCB design process, different types of thermal analysis can be deployed to simulate thermal behavior and ensure proper PCB operation including:

- Temperature analysis
- Worst-case analysis
- Component stress analysis
- Steady-state analysis
- Transient analysis
- Junction temperature analysis
- Joule heating analysis
- IR Drop analysis
- Current density analysis
- Electrical/Thermal co-simulation
- Finite Element Analysis (FEA)
- Computational Fluid Dynamics (CFD)

This eBook provides an introduction into PCB thermal analysis and will discuss how thermal analysis can be incorporated at every stage of the PCB design process, from the schematic to a full system, to reduce overheating and efficiently incorporate thermal management into your PCBs.

TABLE OF CONTENTS

ESSENTIAL HEAT TRANSFER PRINCIPLES FOR PCB DESIGN
CONDUCTION, CONVECTION, AND RADIATION EXPLAINED

Higher packing densities from ongoing miniaturization of electronic assemblies combined with the demands of high-performance and high-power/high-current applications can significantly increase heat generation and lead to thermal management challenges in an electrical circuit. If heat cannot be dissipated properly, it can result in increased circuit temperatures which can affect component and board performance. Heat can be dissipated in three physical ways: conduction, convection, and radiation. The following table provides a summary and comparison of the heat dissipation methods:

	1 CONDUCTION	2 CONVECTION	3 RADIATION
DEFINITION	Transfer of heat between objects in direct contact.	Transfer of heat within fluids or gas.	Transfer of heat by an electromagnetic wave with an infrared wavelength.
REPRESENTS	How heat travels between objects in direct contact.	How heat passes through fluids and gases.	How heat flows through empty spaces.
OCCURRENCE	In solids through molecular collision.	In fluids, through flow of matter.	At a distance and does not heat the intervening substance.
TRANSFER OF HEAT	Solid Substance	Intermediate Substance	Electromagnetic Waves
SPEED	Slow	Slow	Fast
LAW OF REFLECTION & REFRACTION	Does not follow	Does not follow	Follows

Let's take a detailed look at how conduction, convection, and radiation can be seen throughout the PCB design.

THERMAL BEHAVIOR depends on several influences such as the ambient temperature, cooling by convection or additional active cooling and the heat generated by the circuit itself during operation.

CONDUCTION
MANAGING HEAT FLOW THROUGH PCB MATERIALS

1 CONDUCTION

Conduction is the transfer of heat between objects in direct contact. This is the primary form of heat dissipation in PCB design, transferring heat from hot components to cooler areas such as:

Planes & Traces

Copper has high thermal conductivity (~390 W/m*k) and can act to distribute heat horizontally through traces and planes.

PCB Layers

While FR-4 has low conductivity, metal-core PCBs or ceramic substrates can be used in high-power designs for better vertical conduction.

Thermal Vias

Vias provide vertical heat paths from hot components to inner and bottom layers. Additionally, via stitching improves thermal transfer.

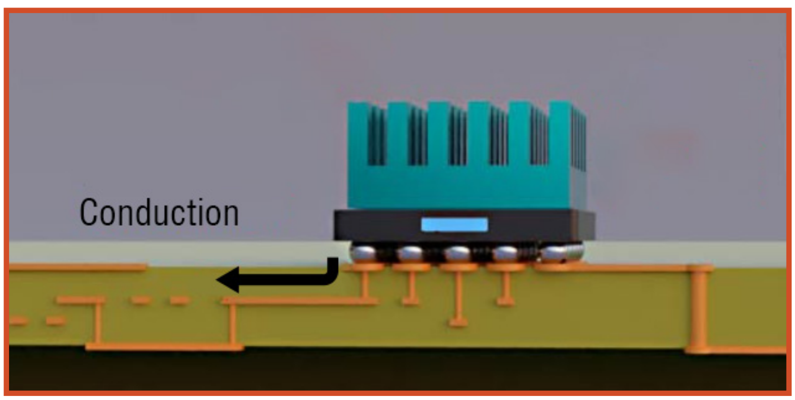
Heatsinks & Enclosures

Heat is conducted through thermal interface materials and mount points to heat sinks and/or metal enclosures.

TIPS FOR IMPROVING HEAT TRANSFER WITH CONDUCTION

To improve heat transfer through conduction, the following methods can be deployed:

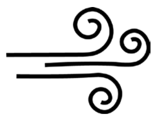
- Use wide copper areas
- Add thermal vias
- Connect to internal copper planes
- Select high thermal conductivity materials
- Minimize thermal bottlenecks



CONVECTION
ENHANCING HEAT DISSIPATION AROUND THE PCB

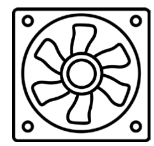
2 CONVECTION

Convection is the transfer of heat within fluids or gases. This is the secondary form of heat dissipation in PCB design, transferring heat from hot components via air flow through:



Natural Convection

Relying on the air movement from temperature differences. This is also referred to as passive cooling.



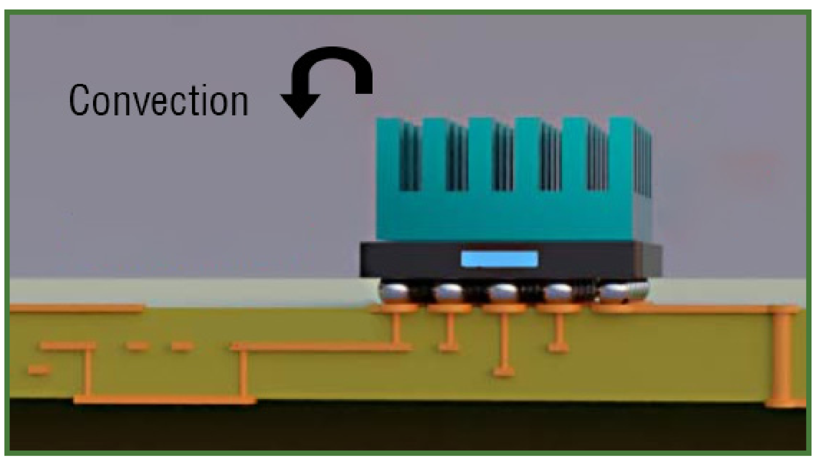
Forced Convection

Using fans or blowers to actively move air across the board. This is also referred to as active cooling.

TIPS FOR IMPROVING HEAT TRANSFER WITH CONVECTION

To improve heat transfer through convection, the following methods can be deployed:

- Maximize exposed surface area
- Use heat sinks
- Orient the board vertically
- Provide airflow paths
- Use fans
- Use vented and open enclosures



RADIATION
HARNESSING EMISSION FOR PCB THERMAL MANAGEMENT

3 RADIATION

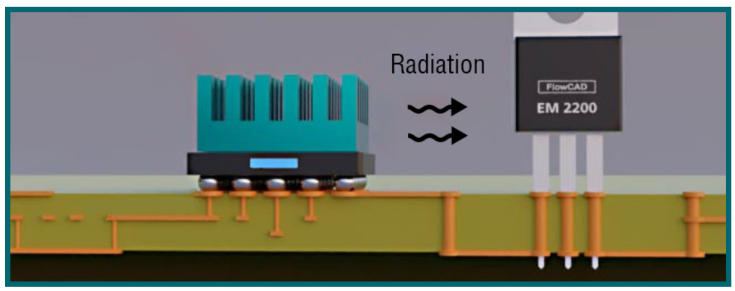
Radiation is the transfer of heat by an electromagnetic wave with an infrared wavelength. Using radiation as a method for heat transfer is especially important in:

- Sealed enclosures with minimal airflow
- Vacuum environments where convection is absent such as aerospace applications
- High-power and high-temperature applications

TIPS FOR IMPROVING HEAT TRANSFER WITH RADIATION

To improve heat transfer through radiation, the following methods can be deployed:

- Increase surface area
- Use high-emissivity coatings
- Expose surfaces to air



Conduction, convection, and radiation can be used throughout the PCB design to dissipate heat. When deciding which method (or combination of methods) to implement, careful consideration should be given to the benefits and downfalls:

	CONDUCTION	CONVECTION	RADIATION
SUMMARY	Transfer of heat through solid materials.	Transfer of heat through fluid motion, typically air or liquid.	Transfer of heat via electromagnetic waves, without need for a medium.
PROS	✓ Efficient in metals ✓ Predictable and easy to model ✓ Enhance with vias & heatsinks	✓ Removal of heat from surfaces ✓ Scales with air/liquid flow rate ✓ Uniform cooling of large areas	✓ Compliments conduction and convection ✓ Works in a vacuum and still air
CONS	✗ Limited by material conductivity ✗ Requires direct physical contact ✗ Not effective for long distances	✗ Dependent on airflow ✗ Requires space for fans/pumps ✗ Can add noise and cost	✗ Dependent on surface area & emissivity ✗ Least efficient method for PCB

When heat can no longer be dissipated through conduction, convection, or radiation circuit and component temperatures can increase, which in turn affect the electrical behavior of the design. To ensure electrical behavior remains consistent, heat transfer must be evaluated throughout the PCB design process.

INCORPORATING THERMAL ANALYSIS

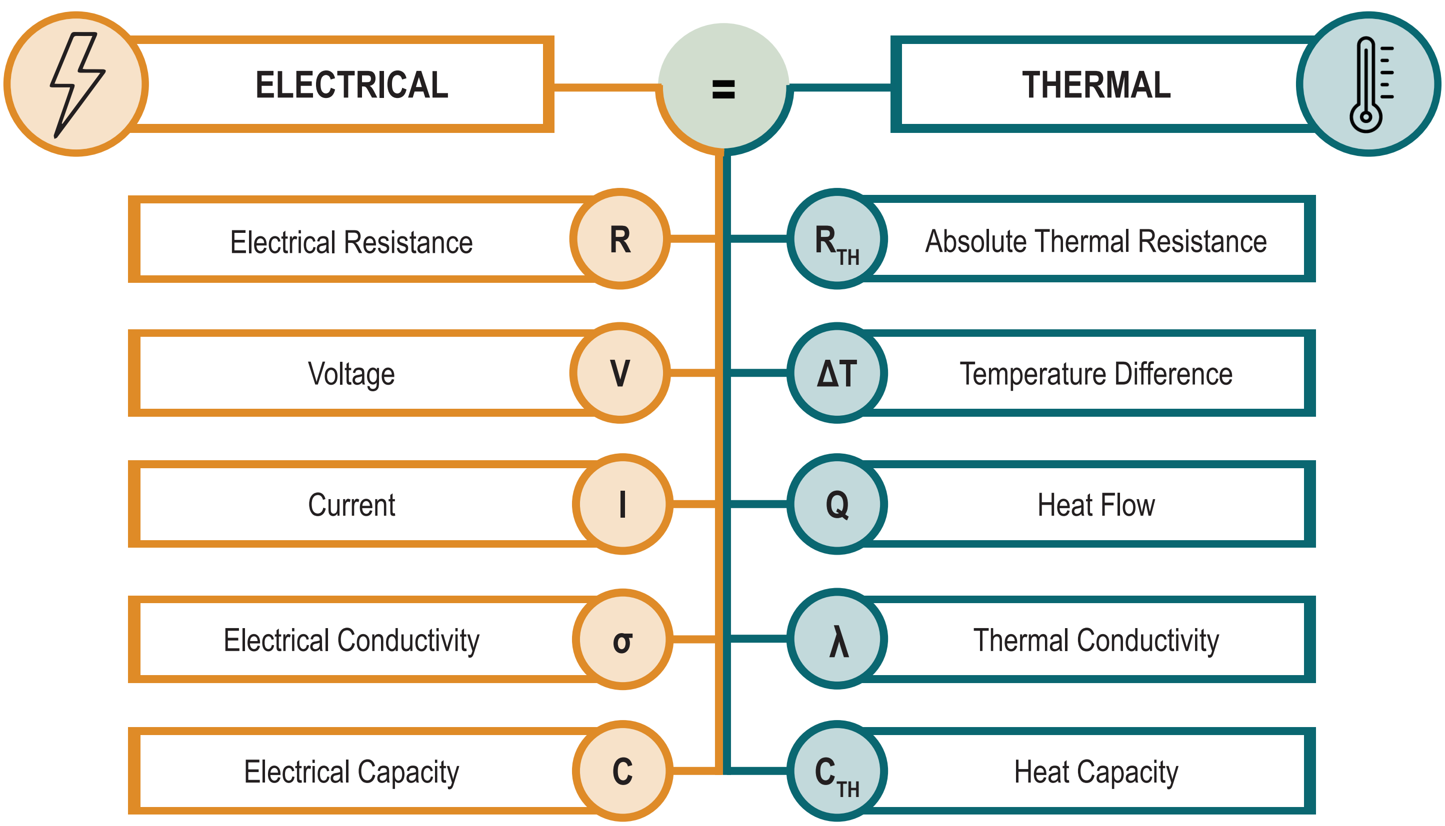
PREDICTING AND CONTROLLING HEAT FLOW IN PCB DESIGN

Increased temperatures on the PCB can have a detrimental effect on circuit performance, such as overheating and thermal damage to solder joints and traces. These issues can be identified and mitigated with thermal analysis.

THERMAL ANALYSIS

The simulation or calculation of temperature distribution across a PCB due to heat generated by components and how heat flows through the board and environment.

To perform thermal analysis, heat transfer must be calculated. When calculating heat transfer, thermal qualities have analogies to those of electrical resistance, which are also reflected in their names. Analogies to electric current appear, which allow the application of Ohm's law and Kirchhoff's rules in heat transfer.



These relationships can be used to better understand the necessary equations to calculate heat transfer for conduction, convection, and radiation.

INCORPORATING THERMAL ANALYSIS

PREDICTING AND CONTROLLING HEAT FLOW IN PCB DESIGN

Conduction, convection, and radiation can be calculated through the following equations to determine the heat transfers in your PCB design.

CONDUCTION

$$Q_{\text{conduction}} = -k \cdot A \cdot \frac{dT}{dx}$$

Where:

K= Thermal conductivity of the material (w/m ·K)

A= Cross-sectional area (m^2)

dT/dx= Temperature gradient across the material

CONVECTION

$$Q_{\text{convection}} = h \cdot A \cdot (T_s - T_\infty)$$

Where:

h= Convection heat transfer coefficient (w/m^2 ·K)

A= Surface area (m^2)

T_S= Surface temperature (°C or K)

T_∞= Ambient air temperature

RADIATION

$$Q_{\text{radiated}} = \varepsilon \cdot \sigma \cdot A \cdot (T^4 - T^4_{\text{ambient}})$$

Where:

ε= Emissivity of the surface

σ= Stefan–Boltzmann constant ($5.67\times10^{-8} W/m^2K^4$)

A= Surface area (m^2)

T= Absolute temperature

$T_{ambient}$= Ambient temperature

Manually calculating temperature distribution across components and the PCB can be time consuming and increasingly complicated with complexity of today's designs- this is where simulations can help.

THERMAL ANALYSIS ACROSS THE DESIGN FLOW

MANAGING HEAT FROM CONCEPT TO FINAL PCB

Thermal simulations rely on advanced software capabilities to calculate the temperature distribution, accelerating the analysis process for designers. To accommodate the varying information at different stages of the PCB design process, multiple types of thermal analysis can be leveraged to obtain a comprehensive view of thermal behavior:

Temperature Analysis

Perform temperature sweeps on your schematic designs to analyze how circuit functionality behaves under various operating conditions.

Worst-Case Analysis

Worst-case scenarios model extreme operating conditions at the component level such as high ambient temperatures.

Component Stress Analysis

Component stress or smoke analysis evaluates whether components in the design are operating within their safe electrical and thermal limits.

Junction Temperature Analysis

Analyze component power dissipation and maximum junction temperatures to calculate the risk of thermal stress and thermal failure.

Steady-State Analysis

Steady-state analysis examines temperature distribution on the PCB under constant power condition.

Transient Analysis

Transient analysis evaluates how the temperature changes over time such as on startup of the device or operation under peak loads.

Coupled Electrical-Thermal

E/T co-simulation combines power dissipation data from circuit simulation with thermal modeling to provide a comprehensive view of thermal behavior.

3D Analysis

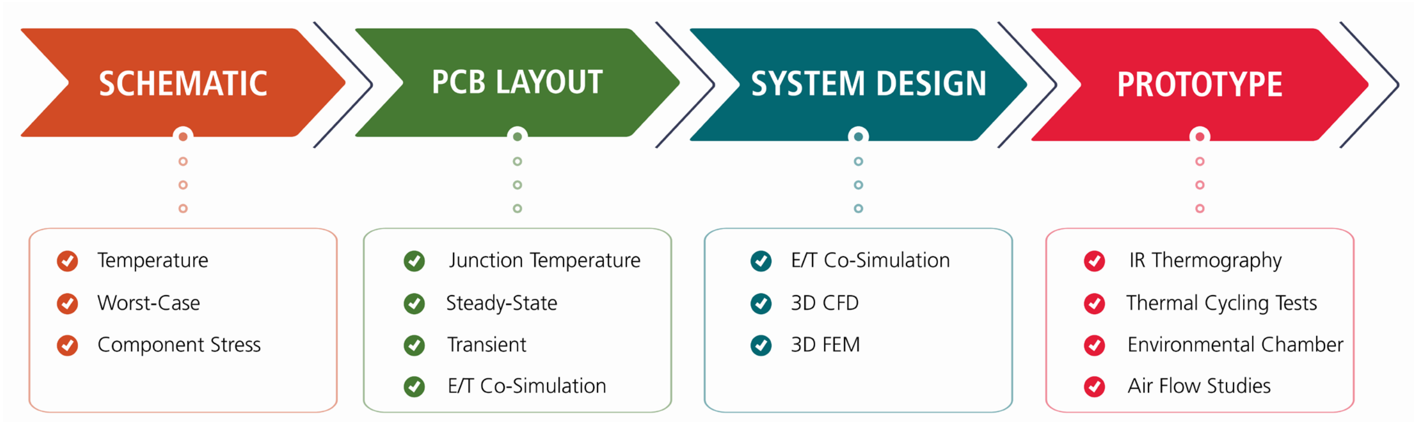
Thermal cooling concepts can be verified with different 3D analysis methods such as Computational Fluid Dynamics (CFD) and Finite Element Modeling (FEM).

The type of thermal analysis deployed throughout the PCB design process is dependent on the PCB design stage and the design information available.

THERMAL ANALYSIS ACROSS THE DESIGN FLOW

MANAGING HEAT FROM CONCEPT TO FINAL PCB

Thermal analysis can be performed throughout the schematic, PCB layout, and system design enabling PCB design optimization for thermal management at every stage:



Depending on the type of thermal analysis required and the stage of the PCB design process, varying information should be included in simulations to emulate real-world behavior. To accurately predict temperature distribution, simulation software can quickly incorporate:

	SCHEMATIC	PCB LAYOUT	SYSTEM DESIGN
SIMULATION OBJECTIVE	Heating of semiconductors during operation.	Heating of the circuit board due to high currents.	Cooling concepts for assemblies with or without housing.
THERMAL ANALYSIS	Temperature Sweeps Worst-Case Smoke Analysis	Junction Temperature Steady-State Transient E/T Co-Simulation	E/T Co-Simulation 3D FEM 3D CFD
CRITICAL INFORMATION	Component Loads Component Derating Power Dissipation Ambient Temperature Environmental Conditions	Component Loads Models of PCB Geometry Heat Sources & Sinks Power Dissipation Thermal Conductivity	Boundary Conditions Heat Sources & Sinks Air Flow Mechanical Enclosures Mechanical Models
AREA OF OPTIMIZATION	Component Selection	Power Delivery Network PCB Layout	External Thermal Management Air Flow

Incorporating this information and performing thermal analysis throughout the design process helps engineers make data-driven decisions and optimize the PCB design beginning in the schematic design.

EARLY INSIGHTS INTO THERMAL BEHAVIOR

THERMAL ANALYSIS DURING THE SCHEMATIC DESIGN PHASE

Thermal analysis can be performed during the schematic phase of circuit development to help designers aid in component selection and resolve heat-related performance issues as temperature can significantly affect component values, semiconductor characteristics, and overall circuit stability. Each type of thermal analysis during the schematic design phase has a specific purpose and use case that provides unique benefits to the PCB design.

Temperature Analysis

Analyzes the effect of environmental and thermal conditions on circuit operation.

Use Case	Benefits
Validate performance and reliability across operating conditions.	✓ Predict real-world behavior ✓ Optimize component selection ✓ Ensure reliability in environments ✓ Identify thermal drift ✓ Prevent thermal runaway

Component Stress Analysis

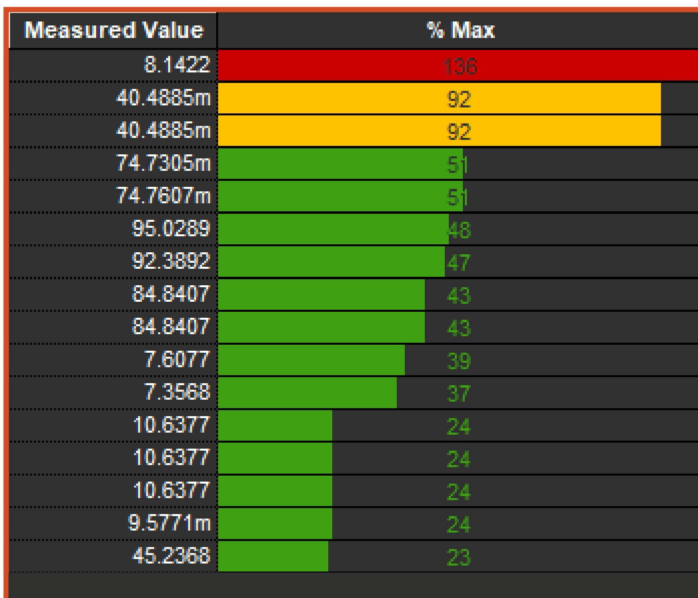
Compares simulated operating conditions against a component's safe operating limits.

Use Case	Benefits
Ensure no component is pushed beyond datasheet limits.	✓ Prevent component damage ✓ Improve reliability ✓ Reduce design costs ✓ Assure compliance ✓ Optimize component selection

Worst-Case Analysis

Evaluates circuit functionality under extreme variations of voltage, temperature, and component tolerances.

Use Case	Benefits
Stress-testing a circuit under extreme but realistic scenarios.	✓ Prevent circuit failure ✓ Optimize PCB yield ✓ Determine design margins ✓ Improve reliability ✓ Ensure safety compliance



Measured Value	% Max
8.1422	136
40.4885m	92
40.4885m	92
74.7305m	51
74.7607m	51
95.0289	48
92.3892	47
84.8407	43
84.8407	43
7.6077	39
7.3568	37
10.6377	24
10.6377	24
10.6377	24
9.5771m	24
45.2368	23

Performing thermal analysis during the schematic design helps to verify circuit behavior, identify potential failures, optimize component selection, and improve reliability of your PCB designs.

DESIGNING FOR HEAT FLOW

THERMAL ANALYSIS IN PCB LAYOUT

Once the schematic is completed, several types of thermal analysis can be performed during the PCB layout to predict and control how heat will flow through the board and components. Thermal conductivity of materials as well as the complete power delivery network (PDN) encompassing copper planes or pours, traces, vias, and more, should be taken into account during thermal analysis. Each type of PCB thermal analysis has a specific purpose and use case that provides unique benefits to the PCB design:

Thermal Conductivity of Common PCB Materials

Materials	λ [W/(m*K)]
Air	0.0262
Aluminum	200-240
Brass	120
Copper	380-400
FR-4	0.2-0.25
Gold	314
Silicon	148
Silver	429
Solder	50

Junction Temperature Analysis

Estimates junction temperatures from power dissipation and thermal resistances.

Use Case	Benefits
Optimize component placement for thermal performance.	✓ Early thermal risk detection ✓ Optimize component placement ✓ Identify overheating ✓ Ensure compliance

Transient Analysis

Evaluates how temperatures change on the PCB over time.

Use Case	Benefits
Analyze power-up, pulsed loads, and/or varying duty cycles.	✓ Identify short-term temp spikes ✓ Validate thermal cycling ✓ Analyze dynamic events ✓ Optimize thermal management

Steady-State Analysis

Visualizes the final temperature distribution on the PCB.

Use Case	Benefits
Analyze hot-spots and the effectiveness of the power delivery network.	✓ Identify long-term operating temps ✓ Locate hotspots ✓ Prevent over & under design ✓ Ensure adequate power supply

E/T Co-Simulation

Models electrical and thermal behavior simultaneously.

Use Case	Benefits
Evaluate the co-dependency between electrical performance and thermal environment.	✓ Early detection of thermal issues ✓ Optimize design decisions ✓ Prevent thermal-induced failures ✓ Improve reliability

Performing these thermal analyses during the PCB layout will provide a comprehensive view of thermal behavior, electrical performance, and PDN design to help prevent hard to find issues *before* manufacturing. Once the PCB layout is optimized for thermal behavior, the full system can be evaluated.

SYSTEM-LEVEL PERSPECTIVE
THERMAL ANALYSIS IN PCB SYSTEM DESIGN

System-level thermal analysis looks at the entire product. This type of analysis focuses on how heat flows and how it is managed across the entire electronic system- not just an individual component or PCB. Instead of focusing solely on a local device or individual board, system-level thermal analysis evaluates how the PCB (or multiple PCBs), enclosures, cooling methods, and the environment interact thermally. Each type of system-level thermal analysis has a specific purpose and use case that provides unique benefits to the PCB design:

E/T Co-Simulation

E/T Co-simulation can model the electrical behavior of the entire system with the thermal response of enclosures, airflow, and multiple PCBs.

Use Case	Benefits
Simulate system-wide electrical behavior and thermal behavior in conjunction.	✓ View electrical-thermal interactions ✓ Predict reliability system-wide ✓ Optimize cooling strategies ✓ Reduce prototype costs

Finite Element Analysis (FEA)

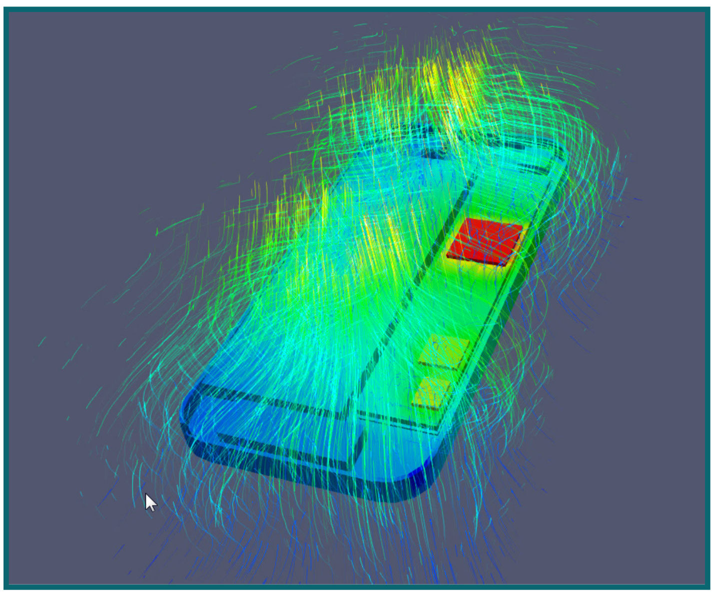
FEA enables designers to simulate conduction using 3D models, meshing, and Fourier's law of conduction to produce a temperature distribution across the product.

Use Case	Benefits
Evaluate temperature fields and gradients to visualize how heat spreads through the assembly.	✓ View thermal stress & expansion ✓ Optimize copper and materials ✓ Predict warpage ✓ Optimize thermal management

Computational Fluid Dynamics (CFD)

CFD enables designers to simulate convection, focusing on airflow and heat transfer within enclosures, racks, and across entire electronic systems.

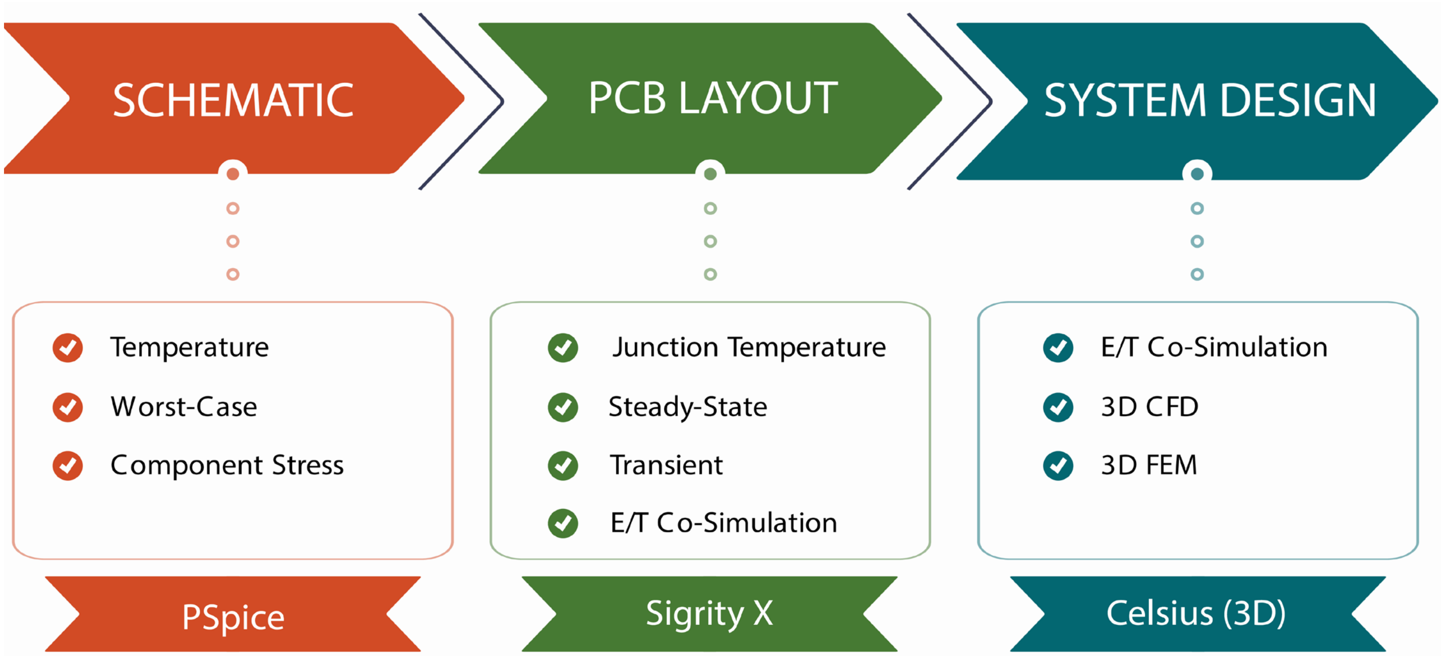
Use Case	Benefits
Model temperature distribution & airflow patterns for the PCB assembly.	✓ Optimize cooling strategies ✓ Validate environmental operation ✓ Identify system-level hotspots ✓ Predict the impact of airflow



When thermal analysis is performed at the system-level, prototype costs can be reduced as it allows designers to virtually test the entire system for proper thermal and electrical behavior and helps ensure end product success.

COMPLETE PCB THERMAL ANALYSIS WITH CADENCE
FROM SIMULATION TO DESIGN INSIGHT

Implementing a holistic approach to PCB thermal analysis will allow designers to optimize thermal behavior at every stage in the design process- from component selection to PCB layout and thermal management. PCB thermal analysis can be achieved throughout the design process with the comprehensive software solutions provided by Cadence:



PSpice is the industry-leading simulation engine that goes beyond basic SPICE analysis and incorporates advanced techniques to provide comprehensive simulation during schematic creation. The advanced capabilities of PSpice allow designers to evaluate:

- Ambient temperature
- Temperature sweeps
- Parametric sweeps
- Worst-case analysis
- Smoke analysis

Sigrity X provides comprehensive signal integrity and power integrity analysis for PCB designs. Minimal setup and step-by-step workflows make it easy for designers to quickly evaluate thermal and electrical behavior directly in the PCB canvas including:

- Thermal analysis
- IR drop & current density
- Steady-state & transient
- E/T co-simulation
- FEM solver

Celsius provides a comprehensive thermal analysis toolset built for electronics. With 2D and 3D solvers, Celsius produces quick, actionable insights which allow designers to identify and solve electronic cooling issues early in the design process by leveraging:

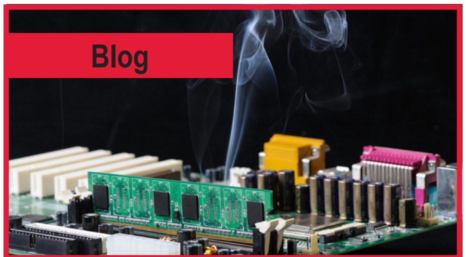
- Multi-purpose solvers
- CFD integration
- Integration to ECAD & MCAD
- Heat exchanger modeling
- What-if analysis

Future eBooks, will delve into the thermal analysis required at each stage of the PCB design process, the parameters that can be analyzed and optimized, tricks and tips to get the most out of your thermal analyses, and suggestions on how you can improve thermal behavior from concept to assembly. Together, these resources will provide a complete toolkit for mastering PCB thermal reliability in complex electronic systems.

LEVERAGING CADENCE FOR THERMAL ANALYSIS

TOOLS, TECHNIQUES, AND RESOURCES FOR PCB HEAT MANAGEMENT

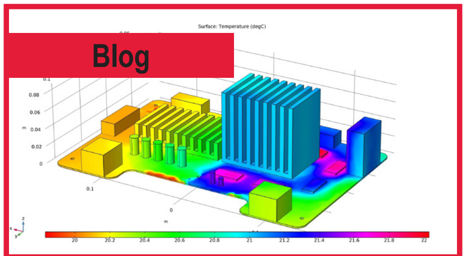
Blog



PCB Thermal Resistance in Heat Transfer

Effective thermal resistance to heat transfer is essential for all designs and critical for high-power boards to ensure stable operation and performance.

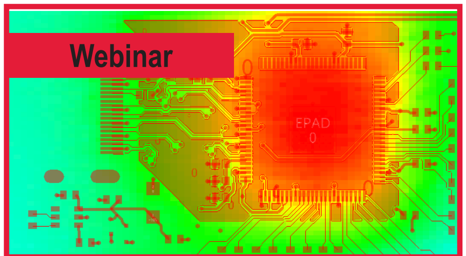
Blog



The Essential PCB Thermal Design Guide

Creating a PCB thermal design guide involves considering factors to manage heat dissipation and ensure the reliability and performance of the board.

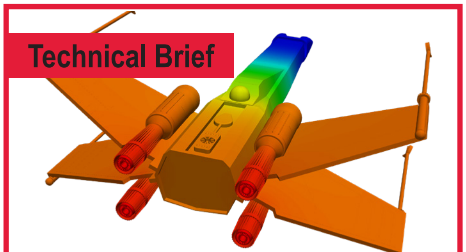
Webinar



Addressing Thermal Design Challenges with In-Design Analysis

Learn several important issues that PCB designers face and the ways in which the Cadence Allegro/Celsius workflow can help streamline the design process.

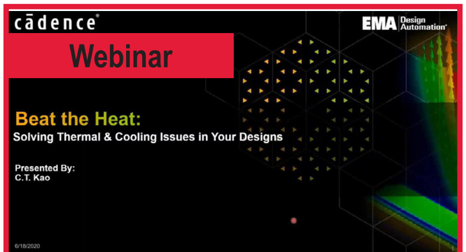
Technical Brief



Rising to Meet the Thermal Challenge

Read how analysis and mitigation of thermal effects have become a key development concern for electronic systems spanning a wide variety of markets.

Webinar



Beat the Heat: Solving Thermal Challenges in Your Designs

Avoid last minute design changes with the Celsius Thermal Solver, which combines FEA and CFD for an entire system analysis.

eBook Series

Coming Soon

Engineer's Guide to PCB Thermal Analysis

This in-depth eBook series provides tips, tricks, and detailed steps to perform PCB thermal analysis at every stage of the PCB design process.

EMA Design Automation is a leading provider of the resources that engineers rely on to accelerate innovation. We provide solutions that include PCB design and analysis packages, custom integration software, engineering expertise, and a comprehensive academy of learning and training materials, which enable you to create more efficiently. For more information on PCB thermal analysis and how we can help you or your team innovate faster, contact us: https://www.ema-eda.com.

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