

Exposed-Pad Power IC Thermal Applications

By

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ABSTRACT

Properly managing the heat generated by power ICs on printed circuit board assemblies is crucial to the successful functioning of a power electronics module. Although sophisticated FEA tools exist for modeling module thermal behavior after the printed circuit board layout has been well defined, there is often only the engineer's own experience to guide him in the initial preliminary pcb layout. For the engineer new to power electronics, this can lead to frustrating multiple design iterations just to manage the waste heat.

This paper provides several heuristic formulas to guide the engineer in determining heat-generating losses and the subsequent thermal management required. Estimation methods are included for achieving successful first order designs relative to the thermal management of power ICs.

Key Words: Thermal Management, Power ICs, Heat Sinking

INTRODUCTION

The integration of analog/mixed signal and power device technology into single integrated circuit packages simplifies electrical circuit design of power modules, yet also creates additional design burden on the electrical/electronics engineer in properly dealing with thermal management requirements impacting the physical design of power modules. Thermal design and optimization is a non-trivial process involving multiple interactive variables, many of which are unknown during the initial design and prototyping stage. Sophisticated FEA (Finite Element Analysis) and dedicated thermal analysis software (the bailiwick of the mechanical design engineer) is often required to achieve the final optimized design.

Towards the goal of assisting the circuit designer in achieving first-time prototype successful operation, this paper provides a heuristic approach to power IC thermal management on standard FR4 printed circuit board modules (with the understanding that more sophisticated techniques and tools will be used in the subsequent design optimization phases). A

secondary goal of this paper is to help the circuit designer gain an intuitive understanding of power IC thermal management.

DEFINITION OF TERMS/SYMBOLS

The following list of symbols and terms are a familiar part of the vocabulary of power electronics, but are restated here with some additional commentary.

- **$R\theta$, Thermal resistance:** an artifice of convenience creating a single parameter equipollent to the complex interaction of factors and multiple parameters governing heat flux as routed to the environment via conduction, convection, and radiation. Its usefulness as a performance comparison parameter is made possible only by testing standards, which severely constrain the test conditions. (MIL-SPEC 883, Method 1012 or SEMI G30-88, JESD51-8, JESD51-2, etc.) Unfortunately, these test constraints limit the predictive accuracy of what results might be obtained from real-world application. At best, thermal resistance, as a parameter, is intended to provide a conservative approximation.
- **$R\theta_{JA}$:-** Junction to ambient thermal resistance, usually stated in " $^{\circ}\text{C}/\text{W}$ " or " $^{\circ}\text{K}/\text{W}$ ".
- **$R\theta_{JC}$:-** Thermal resistance of a packaged component from the surface of its silicon to its thermal tab or metal case, usually stated in " $^{\circ}\text{C}/\text{W}$ " or " $^{\circ}\text{K}/\text{W}$ ". This specification is usually reserved for components with a primary thermal path (e.g., an exposed leadframe die-attach pad, multiple leads connected to the die-attach pad, a metal cased component, etc.).
- **$R\theta_{JB}$:-** An alternative parameter to $R\theta_{JC}$ that takes into account the additional thermal resistance of the solder joint attaching the case of the power IC to the printed circuit board (pcb).
- **$R\theta_{SA}$:-** Thermal resistance from the heatsink-to-ambient air, usually stated in " $^{\circ}\text{C}/\text{W}$ " or " $^{\circ}\text{K}/\text{W}$ ". This specification is usually reserved for manufactured heatsinks, and is often accompanied by graphs indicating the affect of airflow speed on the parameter.
- **$R\theta_{BA}$:-** An alternative parameter to $R\theta_{SA}$ that addresses the heatsinking of an area of exposed printed circuit board copper which is connected to the power IC's primary thermal path.
- **$R_{DS(on)}$:** Drain-source on-resistance when a MOSFET is fully enhanced.

- T_j :- Junction temperature, often assumed to be constant over the die surface.

THE KNOWN VARIABLES

There are a few key variables driving the ultimate thermal design, over which the circuit designer has primary control. Given the starting requirements of the voltages and currents, which must be controlled and/or modulated, the circuit designer makes several initial decisions, which will later drive the required thermal performance. These include:

- Output transistor(s) $R_{ds(on)}$ or $V_{ce(sat)}$ specification
- Switching frequency
- Output dv/dt and di/dt slew rates
- Method of handling induced freewheeling currents and transients

Each of the decisions concerning the above variables will impact the efficiency, and thus the amount of heat the circuit will generate. The circuit designer must be cognizant that every Watt of heat, which is generated, must in turn be dissipated into the environment. These factors play in the heat generation as follows:

- $R_{ds(on)}$ is the controlling factor in I^2R heating
- $V_{ce(sat)}$ is the factor in $V \cdot A$ heating
- Slew rates determine the per/cycle switching loss heating (which is multiplied by the switching frequency)
- Repetitive flyback energy pulses which must be absorbed by the output produce heating (which also is multiplied by the switching frequency)
- Inductive load freewheeling currents produce $V \cdot A$ heating in the conducting diodes.

Therefore, when possible, choosing lower $R_{ds(on)}$ output devices, lower switching frequencies, faster slew rates, etc., will mitigate the thermal requirements impacting the final design.

THE UNCERTAIN VARIABLES

Variables, which are much harder to pin down, yet will have significant impact on the final thermal-mechanical design include:

- Ambient air temperature (T_a)
- Air circulation rate (CFM)
- Board orientation
- Conformal coatings
- Air pressure (altitude) and density (humidity)

- Radiation emissivity of module materials
- Reflective materials in the immediate environment
- Thermal insulative materials in the immediate environment

The temptation is to set some or all of the above uncertainties to worst-case values. However, doing so can yield a design which is overly large, overly costly, and uncompetitive. In the initial design and prototyping stage, a pragmatic approach would be setting the above variables to values easily evaluated on the lab bench, e.g., Ta @ 25C, unconfined space, still air, horizontal orientation, etc. Achieving a working prototype early will lend itself to testing at extremes to determine deficiencies, and can also be used to validate any concurrently run simulations.

THE CONSTANTS

The table below list several key constants, which impact thermal design for power electronics utilizing non-exotic materials and techniques. The numbers are provided as a first order comparison of the materials. Characteristics for mold compound may vary from the material used as an example in the table. Other parameters, especially the conductivity of silicon, vary with temperature.

Material	Conductivity K	Thermal Capacity C _p	Density ρ	Relative Conductivity	Relative Volumetric Heat Capacity
	(W/m K)	(J/kg K)	(kg/m ³)	(W/m K)*	(J/K m ³)*
Mold Compound	0.72	794	2020	0.00200	0.4748
Silicon (at 25C)	148	712	2328.9	0.41111	0.4908
Silver Filled Die Attach	2.09	714	3560	0.00581	0.7524
CU Lead Frame	360	380	8890	1.00000	1.0000
CU Test Board Metal Alloy 42	260	385	8780	0.72222	1.0006
FR-4	0.35	878.6	1938	0.00097	0.5040
Solder SnPb	50	150	8500	0.13889	0.3774
Air	0.03	1007	1.1614	0.00008	0.0003

For this comparison, the baseline for the relative conductivity and relative volumetric heat capacity is that of the copper lead frame. Relative conductivity is a measure of the material's ability to conduct heat, whereas relative volumetric heat capacity is a measure of the material's ability to store heat. Thermal capacitance is the product of thermal capacity, density and volume.

THE LIMITS

The following discussion is the heart of the matter. It is the goal of staying within the limits of operation that drives all aspects of thermal design.

Maximum Allowable Junction Temperature

The most commonly recognized safe operating limit is that of maximum allowable junction temperature. This temperature chosen as the specification limit historically has varied with device type and packaging. Discrete power transistors in plastic packages, for example, were once rated at 150°C but now often carry 175°C ratings. Their metal packaged counterparts have been rated at 200°C for many years. Most mixed signal power ICs are presently rated at 150°C.

Mold Compound Glass Transition Temperature

Mold compound "glass transition" temperature is the temperature at which the mold compound polymer changes from a hard, brittle, glass-like state, to a softened, compliant plastic state. It is a significant limiting factor because it is also the temperature at which the mold compound's thermal coefficient of expansion sharply increases. Once the device exceeds the glass transition temperature, further increases in die temperature rapidly increase mechanical stress on the die and wire bonds. The glass transition temperature of mold compounds typically used in semiconductor packaging is approximately 185°C.

Die-Attach Solder Melting Temperatures

Solders are metal alloys used for physically, electrically, and thermally joining circuit elements. In power ICs, they are often used to attach the die substrate to a copper leadframe. Like all alloys, they have a temperature above which they are fully molten (liquidus temperature) and a temperature below which they are completely solid (solidus temperature). (Note: the two temperatures are only the same in un-alloyed metals and in eutectic alloys). Exceeding the solidus temperature will cause the solder to melt (eutectic solders) or become soft and pasty (non-eutectic solders). At this temperature (which is roughly 210°C for a typical ternary die-attach solder alloy) the die is no longer securely attached to the leadframe, and movement and shorting could occur.

Silicon Shorting Temperature

The third limit is the temperature which silicon becomes intrinsic. At roughly 300°C, thermally generated carriers overwhelm the carriers that are associated with normal operation, and the device becomes essentially shorted. Sustaining this temperature in the presence of any voltage leads to uncontrolled current flow and a further rapid increase in power dissipation. Also, diode V_f falls with increasing temperature and at about 300 degrees C it approaches 0V. At that temperature, any BJT structure, whether it is parasitic or not, has a forward biased base-emitter junction and the transistor itself will begin to conduct substantial current. The only way to stop the current is to remove power.

No Return Temperatures

A device can often recover from the forgoing limits and still operate, if the exposure is brief enough. There are limits above which the device cannot recover. At roughly 660°C aluminum diffuses easily into silicon, spoiling the intended doping levels, and creating permanent damage. Past this point is yet another limit, the melting point of silicon (1400°C) that when reached usually is accompanied by some fireworks and often tiny bits of shrapnel.

Practical Operating Limits

Operation at T_{jmax} is discouraged because doing so leaves no headroom for thermal transients. As indicated above, power ICs are likely to survive rare and brief temperature excursions if they are kept to less than 180°C. It is best to keep the case temperature below 125° C. Also be aware that drain-source, collector-emitter, and cathode-anode leakage increases exponentially with temperature, doubling with approximately every 10°C rise in junction temperature. High leakage will add to the overall thermal load and can contribute to thermal runaway conditions.

The list below summarizes some key temperatures

- 130°C Glass transition of many pcb epoxies
- 150°C Typical maximum junction temperature rating
- 155°C-190°C Mold compound glass transition
- 183°C Melting point of SN63 solder (commonly used to solder components to pcb's)
- 220°C Melting point of die-attach solder
- 300°C Silicon shorts out (goes intrinsic)
- 660°C Melting point of pure aluminum

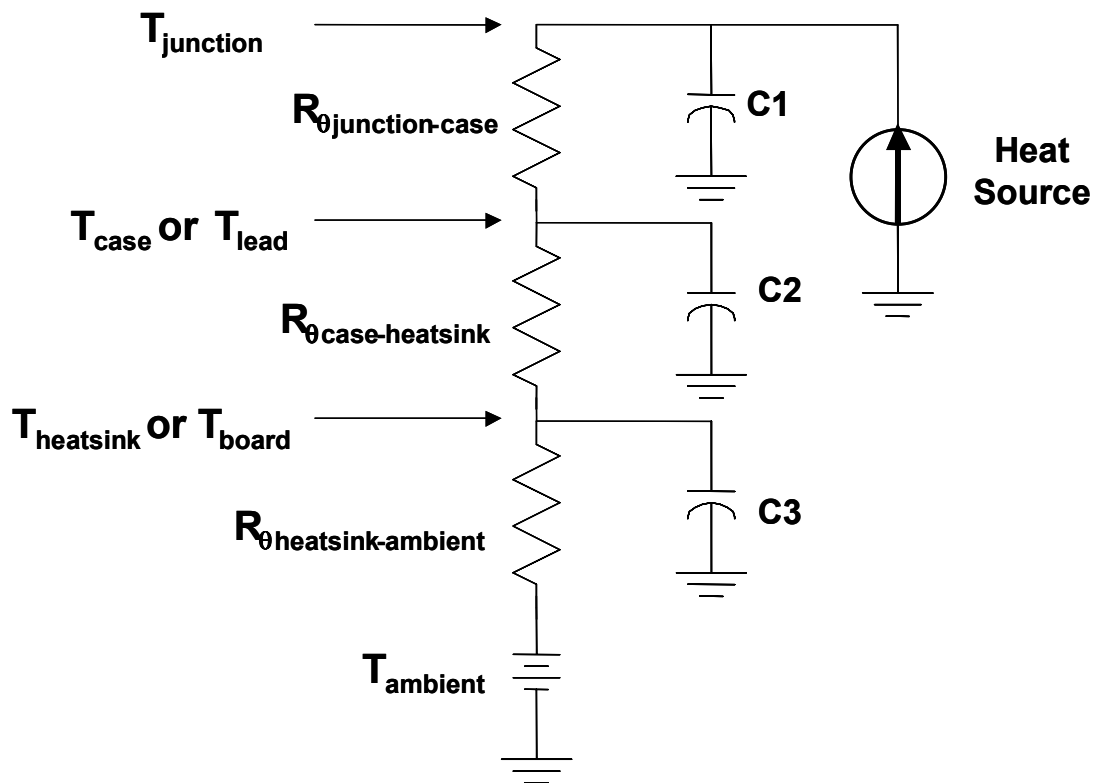
THE FORMULAS

A Caveat

No known practical method will address all possible loads and combinations of conditions. If an expected (realistic) set of conditions can be defined, these convenient formulas for approximating thermal performance can be applied. However, the predicted approximations are relevant to those pre-defined conditions only; extrapolation to other conditions is often not straightforward. A more rigorous analysis often involves empirical testing of prototypes supported by finite element analysis simulations.

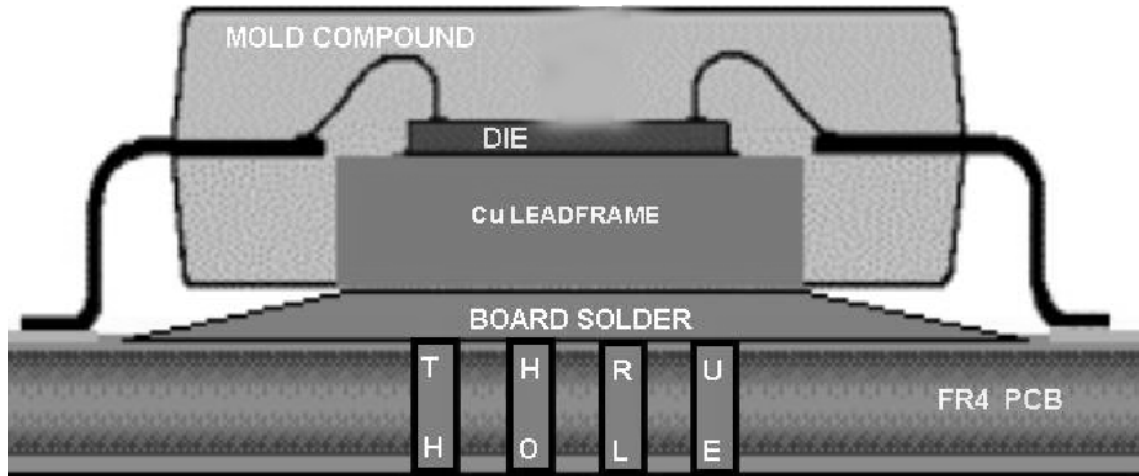
Thermal Resistance and Capacitance

The conceptual parameters of thermal resistance and thermal capacitance enable the engineer to evaluate thermal behavior using an analogous electrical circuit as show below:



Simple, Lumped Thermal Model of a Semiconductor Assembly

The diagram below illustrates in cross-section the physical elements of a typical power IC thermal circuit.



Typical Power IC Thermal Circuit Physical Elements

Note that it is the DIE that generates the heat. The surrounding elements (leadframe, mold compound, solder, printed circuit board, etc.) carry the heat away from the die and into the ambient environment. The heat that is generated by the die is a function of its power losses over time, i.e.:

$$P_d = \frac{\text{Heat Flux}}{\text{time}} = \frac{Q}{t}$$

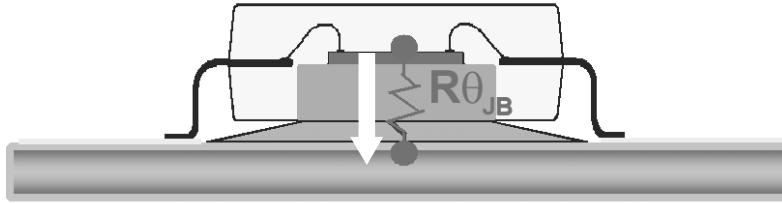
The thermal capacitance is associated with the mass and specific heat properties of the materials within the power IC package. Because there is thermal capacitance as well as thermal resistance, there is a thermal time constant that can be stated as:

$$\tau_\theta = R_\theta C_\theta$$

where

$$C_\theta = P_d * \frac{dt}{dT} = C_p * \rho * \text{Volume}$$

Let's consider the parameter of junction-to-board thermal resistance. The figure below schematically represents the thermal path considered.



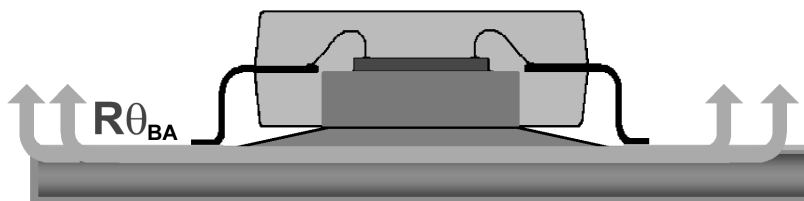
Thermal Resistance Junction-to-Board

Note that the path is from the die, through the die-attach solder, through the leadframe, through the circuit board solder, to the surface copper of the printed circuit board. This thermal resistance is a function of the temperature delta from die-to-board versus the power dissipation, i.e.:

$$R_{\theta_{JB}} = \frac{T_J - T_B}{P_D}$$

Where T_B is measured at the hottest spot on the board.

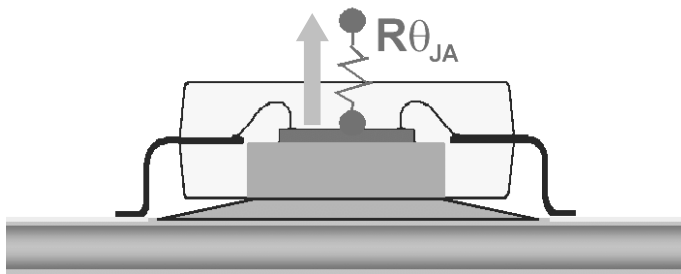
The above parameter is used with the $R_{\theta_{BA}}$ parameter (shown below) to complete the thermal path to ambient.



$$R_{\theta_{BA}} = \frac{T_B - T_A}{P_D}$$

Thermal Resistance Board-to-Ambient

Similarly, the thermal resistance from junction-to-ambient air for a typical power IC package is illustrated and defined in the figure and formula below:



$$R_{\theta JA} = \frac{T_J - T_A}{P_D}$$

Thermal Resistance Junction-to-Ambient

Determining Power Dissipation

Estimating the power dissipation is the first step in power IC thermal management. Summing the average contribution of all sources of power dissipation and assessing that power's effect on the average junction temperature is the goal of this analysis. We'll proceed by breaking the analysis into steps based on the contributing sources of operating losses.

First, there is the contribution due to conduction losses. These are easily computed as the $I^2 R_{DS(ON)}$ or VA product of the circuit's power transistors when in the "ON" state.

Second, one needs to assess the contribution of the switching losses. Two suggested solutions to estimating switching losses are:

- Estimate losses for the turn-on and turn-off edges by multiplying V_{ds} and I_d oscilloscope waveforms and integrating the resultant waveform over the switching transition.
- Use a reliable electrical simulation to assess turn-on and turn-off switching losses.

Once the switching losses and the energy losses per cycle are known, simply multiply by the switching frequency to obtain the contribution of the switching losses to the average power dissipation. In many cases, on-state and switching losses are the only significant heat generating losses the power IC incurs.

Thirdly, estimate power dissipation associated with self-clamping or avalanche losses. The complexity of this task depends on the type of load the power IC is controlling. Motor and solenoid loads consist of electrical, mechanical and magnetic elements, and can give some bizarre appearing waveforms to the uninitiated. Because of these numerous factors, the two suggested approaches for estimating switching losses provided above also apply here. Once the energy per cycle is estimated, it is a simple matter to determine its contribution to average power dissipation. (One reason it is easier to measure, rather than calculate, the clamping/avalanche losses, is because the inductance of a solenoid or other inductive load is likely to vary with test frequency or rate of applied voltage, mechanical state of the solenoid (open or closed) and coil temperature. These, plus the most important factor, coil current magnitude, are likely to change throughout the clamping/avalanche interval.)

Fourthly, estimate the average power dissipation caused by the conduction loss of the body diode (the inherent diode in a MOSFET's structure). The contribution of diode reverse recovery losses are usually trivial unless the switching frequency and slew rates are high, e.g., H-bridge motor control circuits operating at high voltage and high switching frequency are candidates for gauging body diode reverse recovery losses.

Determining Die Temperature

After all the contributions to the power dissipation are known, simply sum them and then use the thermal resistance and formula below to estimate the die's average junction temperature:

$$T_J = R_{\theta} \bullet P_D + T_A$$

Note: The thermal resistance considered above is the composite thermal resistance, i.e., the thermal resistance resulting when

all the heat paths are taken into account. When we consider the heat paths discussed previously, the composite thermal resistance becomes:

$$R\theta = R\theta_{JB} + R\theta_{BA} \parallel R\theta_{JA}$$

OR

$$= ((R\theta_{JB} + R\theta_{BA}) \cdot R\theta_{JA}) \div (R\theta_{JB} + R\theta_{BA} + R\theta_{JA})$$

In most cases, the thermal path via the heatsink is much lower than the device package $R\theta_{JA}$, and so $R\theta_{JA}$ is ignored.

HEURISTICS and INTUITION

Like any endeavor, experience and practice provides not only a honing of skill, but eventually a certain intuitive feel for the correct approach and outcome. An engineer with years of experience in power electronics can develop an insight that transcends the formulas, and can serve as a "computation sanity check" for the calculations. Towards the end of jump-starting that insight for engineers less acquainted with power, we submit the following mental exercises for their consideration.

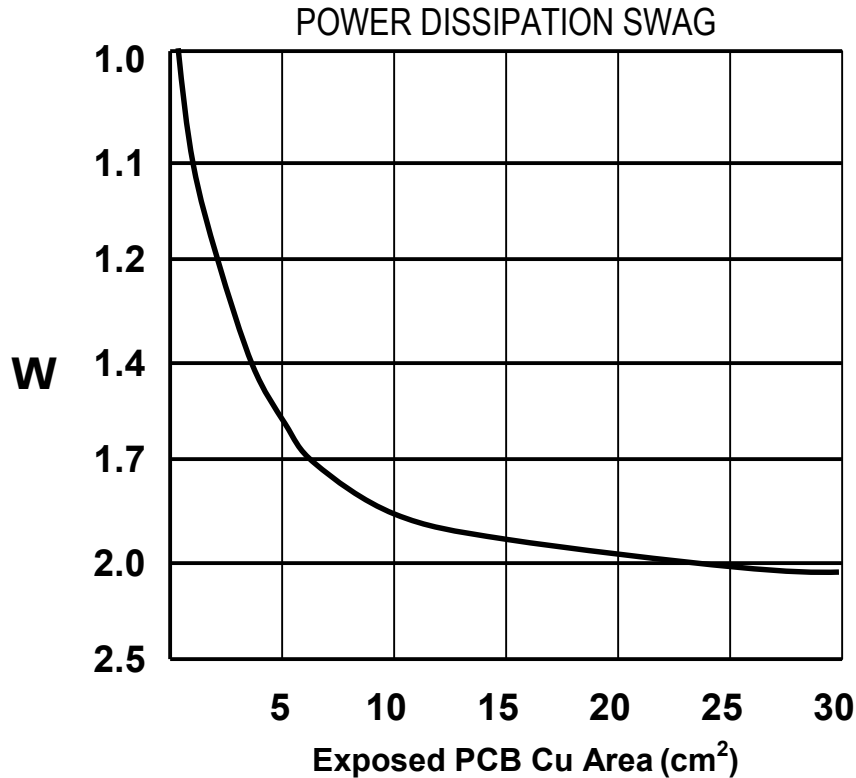
- **Visualizing a Watt of Heat:** One Watt of heat, steady-state, is by definition one Joule of energy every second. This amount of heat energy, if concentrated into a small space, can raise the temperature of solids very rapidly. Picture in your mind a 5W nightlight bulb... one cannot hold their hand closed about it very long without getting burned, yet it has approximately 5 square inches of surface area, each dissipating only one Watt. When left exposed to ambient air, this same surface area is sufficient to keep its surface relatively cool (less than 60°C) via conduction, convection, and radiation.
- **Visualizing Thermal Conductivity:** Metal is typically an excellent conductor of heat. Visualize a frying pan filled with sizzling oil as you fry some diced onions. If the pan has a plastic handle, you have no problem holding it. If the pan is an old-style cast iron skillet with cast iron handle, you cannot pick it

up unless you use an oven mitt to insulate your hand from the metal. In the first instance, the plastic handle, even if its temperature has stabilized at the 150°C of the hot oil, cannot conduct the heat into your skin as fast as your skin (and subcutaneous vessels) conducts the heat away from the handle surface. The cast iron handle, on the other hand, would conduct the heat into one's hand much faster than one's hand could carry the heat away, and pain would be the result. The thermal conductivity of plastics (including mold compounds) is on the order of 0.5 W/mK. The thermal conductivity of copper is 360 W/mK and solder (tin/lead) is 50 W/mK.

- **Visualizing Temperature:** Imagine you are washing dishes, and you have the water as hot as you can tolerate. The temperature is probably about 60°C, if your threshold of pain is typical. In another scenario, you have brewed for yourself a fresh pot of tea; you are careful not to spill hot steeping tea on yourself, as it is 98°C and could blister your skin. These are familiar temperatures. For comparison, if a semiconductor package, that is developing one Watt, has an $R_{\theta_{JC}}$ of 25°C/W, when the case is at 85°C (well above your threshold of pain, yet not hot enough to blister instantly), the die will be at 110°C (which is operationally acceptable).

The formulas presented in this paper are well known useful approximations. Even so, in the conceptualization stage of a design, it is often advantageous to be able to "guesstimate" the printed circuit board heatsinking area required without running through the calculations. A graph is presented here which is useful in obtaining first-order rough approximations. It is presented in terms of power dissipation vs. circuit board heatsink area, as this is how the question is often posed in technical information requests. E.g., "How much board area will this IC require to dissipate 2W?" It is, of course, difficult to answer such a seemingly simple question, when no other information is supplied. Accordingly, a graph such as this

contains many assumptions (e.g., die temperature = 125°C, $T_A = 25^\circ\text{C}$ with natural convection, 10°C/W power $R_{\theta_{JB}}$, etc.). Nevertheless, the graph represents a **Scientifically Worthy Approximate Guess** at the power dissipation.



A FINAL ANALOGY

Thermal analysis is an exercise in analogies. The formulas are simple single-dimensional analogies to complex three-dimensional functioning. The parameters are severely constrained linear analogies to tough-to-measure physical performance. The operating limits are based on statistical data, analogous to acceptable device reliability and operating life. And so on. These analogies, nevertheless, embody sufficient isomorphism with the end physical application to be considered indispensable tools.

For the reader's consideration and encouragement, we conclude with this final analogy: When a Golfer hits a ball from the first tee, his ideal goal is a hole-in-one. However, the Golfer is not really expecting to accomplish this feat, and recognizes that successive iterations will be required, each one bringing the ball closer to the cup. Similarly, the first iteration of a thermal design is not likely to achieve full

optimization, and will necessarily require additional refining iterations.

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