

Thermal Considerations for TMS320DM64xx, TMS320DM64x, and TMS320C6000 Devices

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ABSTRACT

As integrated circuit (IC) components become more complex, the challenge of producing an end product with superior thermal performance increases. Thermal performance is a system level concern, impacted by IC packaging as well as by printed circuit board (PCB) design. This application report addresses the thermal considerations for the TMS320DM64xx, TMS320DM64x, and TMS320C6000™ DSP devices.

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Grafoil is a registered trademark of UCAR Company .

1 Introduction

As technology advances, the demand increases for more highly complex ICs with faster clock rates, smaller packages, higher pin counts, and increased reliability for a lower cost. This complexity creates higher power consumption and increased thermal challenges across IC component products. Many of these IC packages make it difficult to produce an end product that meets the thermal limitations of the product components. The following IC package features can contribute to increasing the thermal output:

- Decreased package size
- Decreased die size
- Increased pin count
- Increased system complexity/integration
- Faster clocks
- Processes with increased leakage
- Need for lower cost
- Higher reliability/lower junction temperatures

This application report discusses the thermal considerations of the DM64xx and DM64x™ digital media processors, and the C6000™ DSP devices and offers guidance on thermal performance analysis, as well as options to improve your thermal design.

2 General Thermal Considerations

When designing a system with DM64xx, DM64x and C6000 devices, consider the following items:

- Potential maximum power consumption in the intended application. This can be determined from the device-specific power application report.
- Maximum rated case temperature or junction temperature specification. This can be determined from the device-specific data manual.
- Typical θ_{JA} in real systems. This depends on both the specific device used, and the thermal design of the overall system.

The device power consumption varies across applications, so you should use the device-specific power consumption summary to calculate power consumption for a specific application.

2.1 Junction Temperature versus Case Temperature

In the device-specific data manual, TI specifies a maximum operating temperature. The maximum operating temperature specified in the data manual is either a maximum operating case temperature or a maximum operating junction temperature. To ensure device reliability and proper operation, do not exceed the maximum operating case or junction temperature specified in the data manual.

Although the only thermal requirement TI specifies is a maximum operating case or junction temperature, other system features such as PCB characteristics, PCB layout, and ambient temperature can also contribute to the thermal performance of the system. These must be designed to meet TI's maximum case or junction temperature specification. For instance, the most commonly used thermal parameter, θ_{JA} , is not just a function of the device package, but is also of the characteristics of the PCB on which it is mounted.

3 Thermal Definitions

The next few sections summarize the usage of the thermal resistances discussed in the device-specific data manual. See the data manual for more information.

3.1 Overview

Figure 1 shows a simplified representation of the thermal path from the junction of the die through both the top and bottom of the package. As shown here, the thermal path can be modeled as an equivalent electrical circuit. In this approach, power in watts is equivalent to current in amps, temperature delta in degrees is equivalent to voltage drop, and thermal resistance in °C/W is equivalent to electrical resistance in Ω s. Therefore, a thermal resistance can be calculated as the temperature delta between node X and node Y, divided by the power.

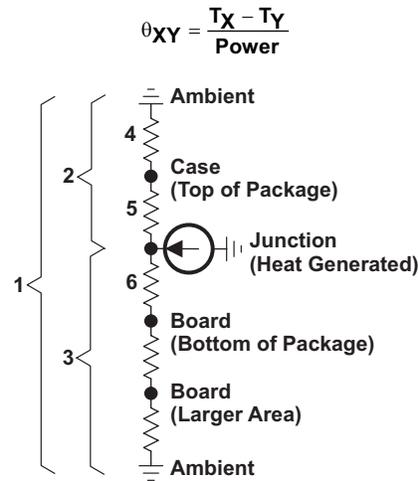


Figure 1. Thermal Path

The resistances shown in [Figure 1](#) relate to the thermal resistances of the package and system as follows:

1. $\Theta_{JA, \text{effective}}$: Total resistance of the whole system from the die (junction) to ambient air
2. Total θ through top (θ_{top}) of device to environment (including heat sink if used)
3. Total θ through bottom (θ_{bot}) of device and PCB to environment
4. Θ_{CA} : Resistance from top of device through air or heat sink to environment
5. Θ_{JC} : Resistance from die (junction) to the top of the package (case)
6. Θ_{JB} : Resistance from die (junction) to the board (near to the device), as defined by JESD 51-8

The resistances in steps 2 and 3 are not defined in the device-specific data manuals, but are mentioned here because they are useful in heat sink calculations.

3.2 **Theta-JA (Θ_{JA}) Junction to Ambient**

Θ_{JA} is the difference in junction temperature to ambient temperature, divided by the operating power. As discussed in [Section 3.1](#), θ_{JA} is not a constant but a function of any and all factors that influence the thermal resistance between the junction of the device and the ambient environment. Some key factors that influence θ_{JA} are:

- PCB design and layout
- Chassis/box design
- Venting
- Altitude

In the device-specific data manual, θ_{JA} is a measurement of the thermal performance of an IC package mounted on a specific test coupon. TI conducts measurements on systems defined in the following JEDEC specifications:

- JEDEC theta-JA measurement conditions defined in JESD51-2
- 1s0p or *low effective thermal conductivity* test board defined in JESD51-3
- 2s2p or *high effective thermal conductivity* test board defined in JESD51-7

Θ_{JA} provides a metric by which the relative thermal performance of a package can be compared. Thus, the thermal performance of a Texas Instruments device can be compared to a device from another company, as long as the other company follows the JEDEC conditions as defined in the specifications.

These θ_{JA} values are not intended to provide an accurate estimate of the temperature difference between junction and ambient in a real system. Instead, the θ_{JA} value as defined by JEDEC provides a means of comparing the thermal performance between packages. Methods for estimating this temperature difference are discussed in the next section.

3.3 **Theta-JC (Θ_{JC}) Junction to Case**

Θ_{JC} is the difference in junction temperature to case temperature, divided by the operating power in a specified environment. There is not currently a JEDEC specification for this parameter, although one is in progress. Θ_{JC} is measured by putting a mounted package up against a Cu block cold plate to force heat to flow from the die through the mold compound into the Cu block.

As described later in this application report, this parameter is useful when a heat sink is applied to a package. Without a heat sink, Θ_{JC} should not be used to predict junction temperatures. When case temperatures are measured in a system, and junction temperatures are then calculated from the following equation, pessimistic junction temperatures are obtained.

$$T_{\text{Junction}} = T_{\text{Case}} + (\text{Power} \times \Theta_{\text{JC}})$$

3.4 **Theta-JB (Θ_{JB}) Junction to Board**

Θ_{JB} is the difference in junction temperature to board temperature, divided by the operating power in a specified environment. Θ_{JB} provides an overall thermal resistance between the die and the PCB. It is the difference in the junction temperature and the PCB temperature at the PCB perimeter (closest to the die) when the PCB is clamped in a cold plate structure. JEDEC standard JESD 51-8 defines Θ_{JB} measurement conditions and board measurement locations.

3.5 **Psi-JT (Ψ_{JT}) Junction to Top of Package**

Ψ_{JT} is the difference in junction temperature to case temperature at the top center of the package, divided by the operating power. Ψ_{JT} has the same measurement points and units as Θ_{JC} ; however, Ψ_{JT} is measured when the package is mounted on the test PCB, allowing power to partition itself into any path. Note that Θ_{JC} is a true thermal resistance, while Ψ_{JT} is measured under conditions that are closer to real world use.

Ψ_{JT} is primarily used to calculate the junction temperature from a measured case temperature via the following equation:

$$T_{\text{Junction}} = T_{\text{Case}} + (\text{Power} \times \Psi_{\text{JT}})$$

4 **Rough Estimate of System Thermal Performance Using Theta-JA (Θ_{JA})**

Before finalizing the system layout and PCB design, you must plan to meet the maximum operating temperature documented in the data manual. As described in [Section 2.1](#), this maximum operating temperature is specified as either a case or junction temperature. This requires a preliminary assessment of either the case or junction temperature in context of the entire system. The most accurate method for evaluating the case temperature and junction temperature prior to completion of the system layout is to use detailed thermal models of the final system. One service provider that TI is aware of who can assist with system thermal modeling and analysis is Applied Thermal Technologies, see <http://www.thermalcooling.com/>.

Although thermal models are the most accurate method for predicting the case or junction temperature of the device in a specific application, you can also make a less accurate estimate by comparing TI's JEDEC Θ_{JA} data measured on two JEDEC defined test boards:

- Θ_{JA} (no airflow) on a high effective thermal conductivity test board defined in JESD51-7
- Θ_{JA} (no airflow) on a low effective thermal conductivity test board defined in JESD51-3

Θ_{JA} varies between application scenarios because it is not just a function of the device package alone, but also a function of other factors in the system. Therefore, the temperature rise above ambient as measured under JEDEC test conditions is different from the temperature rise above ambient in a real application. To differentiate the use of the term Θ_{JA} as measured in JEDEC conditions versus that estimated or measured in a real application, TI uses the term $\Theta_{JA, \text{effective}}$ to describe the Θ_{JA} in a real application.

The window defined by the θ_{JA} values provided under the JEDEC defined test conditions can be used as a very rough estimate of $\theta_{JA, \text{effective}}$ for a specific application, although applications could fall anywhere in that window and even outside that window. Ultimately, $\theta_{JA, \text{effective}}$ is best gathered from system thermal modeling or actual measurements in the application environment.

Once $\theta_{JA, \text{effective}}$ has been estimated, use the following equation to generate a rough estimate of junction temperature:

$$T_{\text{Junction}} = T_{\text{Ambient}} + (\text{Power} \times \theta_{JA, \text{effective}})$$

Note: To be consistent with JEDEC measurement techniques, as well as referencing the most independent and static temperature point, TI recommends measuring the final system ambient temperature outside the enclosure, rather than inside the enclosure, which may be influenced by heating from other parts.

Devices with a specified maximum operating case temperature may require an additional step to estimate case temperature. For devices that have a low ψ_{JT} value (less than 0.2 °C/W) specified in their data manual without a heat sink, the difference between case temperature and junction temperature is typically less than 1°C. Therefore, you can assume that case temperature is approximately equal to junction temperature.

$$T_{\text{Case}} \approx T_{\text{Junction}} = T_{\text{Ambient}} + (\text{Power} \times \theta_{JA, \text{effective}}) \text{ (Used for devices with low } \psi_{JT} \text{)}$$

For devices that have higher ψ_{JT} values (higher than 0.2 °C/W), there is a larger delta between case temperature and junction temperature. Use the following equation to estimate case temperature.

$$T_{\text{Case}} = T_{\text{Junction}} - (\text{Power} \times \psi_{JT}) \text{ (Used for devices with low } \psi_{JT} \text{)}$$

The power included in the above equations should be estimated for the specific application using the device-specific power application report.

5 Case Temperature Measurement

Once the system has been finalized and manufactured, perform a case temperature measurement to ensure that you have not exceeded the maximum case temperature specification of the device.

Devices with a specified maximum operating junction temperature require an additional step to determine the junction temperature from the measured case temperature. Use the following equation without a heat sink:

$$T_{\text{Junction}} = T_{\text{Case}} + (\text{Power} \times \psi_{JT})$$

5.1 Case Temperature Measurement Without a Heat Sink

Case temperature is the hottest temperature on the top of the device and should be measured at the center of the device top or lid. In order of accuracy, you can measure the case temperature with an IR camera, a fluor optic probe, a thermocouple, or an IR gun with a maximum field view of 4mm diameter.

When using either a IR camera or IR gun, be sure to correct the reading for the emissivity of the surface being investigated. See your instrument's documentation for details.

If you choose a thermocouple as the measurement technique, use a fine gauge wire (36 to 40 gauge, J or K wire) to minimize the local cooling from the thermocouple. The thermocouple should be attached to the center of the package surface (± 1 mm) with a bead of thermally conductive epoxy no larger than 2x2 mm on a side. Taping the thermocouple to the package surface is not recommended. To minimize the heat sinking aspects of the thermocouple, the wire should be dressed along the diagonal of the package, down to the PCB surface, and over a minimum distance of 25 mm before lifting from the PCB. The thermocouple wire can be tacked to the PCB for this routing purpose using tape. Use of improper thermocouple wire gauge can create errors in the measurements of 5-50%.

5.2 Case Temperature Measurement With a Heat Sink

Measuring case temperatures with heat sinks applied is difficult because the heat sink covers the surface to be measured. To measure the case temperature with a heat sink applied, use the following procedure:

1. Drill a hole with a diameter of 1 mm or less in the heat sink, so that the hole is at the center of the package when the heat sink is attached. Be sure to drill the hole through the heat sink before attaching it to the package. If a pressure sensitive adhesive or epoxy is used to attach the heat sink, drill through this adhesive. Be sure there are no burrs or other material that would interfere with the mating surfaces.
2. Attach the heat sink to the package. If an epoxy is used for the attachment, fill the hole drilled in Step 1 with a wax, foam, or other material to ensure the hole is not filled with the epoxy. Be careful not to contaminate the heat sink attach surface with this material.
3. Fill the hole with thermal grease. If the hole was plugged to avoid epoxy filling, be sure to unplug the hole.
4. Thread a fine gauge thermocouple of the type described in [Section 5.1](#) into the hole and secure with a drop of epoxy or tape.

5.3 Case Temperature Measurement: Accounting for Leakage Variations

The resulting case temperature of the device that is measured in the finalized system is dependent on the power consumption of the device in the specific application. To determine the maximum case temperature measurement, you must account for the worst case power consumption of the device for the finalized product.

The power consumption of the device can be broken down into the sum of two components: active power and static (also called leakage) power. Static power varies across voltage, temperature, and manufacturing processes. The device-specific power consumption summary spreadsheet takes into account the static power consumption from the strong units (representative of maximum end of static power consumption on production units). The spreadsheet calculates the worst case static power consumption for a given case temperature. The obtained value can then be used to calculate the final worst case total power consumption.

The following method describes how to measure and use the worst case static power consumption:

1. Measure the case temperature using the method described in [Section 5.2](#).
2. Measure ambient temperature. TI recommends measuring the ambient temperature outside the enclosure, rather than inside the enclosure, which may be influenced by heating from other parts.
3. Measure total power consumption of the device in the finalized application.
4. Measure the static power consumption of the device at the case temperature measured in Step 1.
5. Calculate the active power consumption in the finalized application.

Active power = Total power(step 3) - Static power(step 4)

6. Calculate the $\theta_{JA, effective}$ of the finalized system using the following equations:

$$T_{Junction} = T_{Case}(step\ 1) + (Power(step\ 3) \times \Psi_{JT})$$

$$\theta_{JA, effective} \approx \frac{T_J(step\ 6) - T_A(step\ 2)}{Total\ Power(step\ 3)}$$

7. Use the power application spreadsheet to determine the maximum static power consumption.
 - a. For devices with a specified maximum operating case temperature in the data manual, use the power application spreadsheet to determine the maximum static power consumption at the case temperature measured in Step 1.
 - b. For devices with a specified maximum operating junction temperature in the data manual, use the power application spreadsheet to determine the maximum static power consumption at the junction temperature calculated in Step 6.

8. Recalculate the maximum total power consumption of the device.

$$\text{Max Total Power} = \text{Active Power}(\text{step 5}) + \text{Max Static Power}(\text{step 7})$$

9. Recalculate the junction and/or case temperature, accounting for maximum total power consumption.

$$T_J = T_A(\text{step 2}) + (\text{Total power}(\text{step 8}) \times \theta_{JA, \text{effective}}(\text{step 6}))$$

$$T_{\text{Case}} = T_{\text{Junction}}(\text{step 9}) - (\text{Power}(\text{step 8}) \times \Psi_{JT})$$

6 System Thermal Improvements

As described in this application report, the thermal performance of a system is affected by both the device and the PCB layout. The following items can improve a system's ability to dissipate heat. This is not an exhaustive list and each item should be evaluated to see if it is a good fit for an application.

- Maximize thermal vias in PCB under the device (connected to GND BGA balls and GND plane in PCB)
- Spread out parts on the PCB (including power supplies, etc.) that are dissipating >500 mW
- Ensure the power and ground planes that connect to the device are relatively continuous for a 25-50 mm radius around the package
- Add venting to the chassis, especially near the DSP
- Add screws from the PCB to chassis near the DSP
- Use thermal gap filler material between the top of the device and the chassis, especially if the chassis is metal. The gap between the PCB and chassis should be less than 3 mm for this cooling scheme to be effective. The gap filler conducts heat from the PCB to the system chassis, where it can be more effectively rejected from the system. You can obtain thermal gap fillers with thermal conductivities ranging from 0.5 W/m-°C to 3 W/m-°C from many sources, including The Bergquist Company. The following link references one of their products:
http://www.bergquistcompany.com/tm_gap_pad_detail.cfm?oid=110236.
- Use a metal clip between the top of the device and the chassis
- Add a heat sink to the device (optimize heat sink type based on airflow)

7 Thermal Improvements via a System Heat Sink

Heat sinks are one of the most commonly considered thermal improvement methods. In this application, the term heat sink is defined as both an off-the-shelf heat sink purchased from a vendor, as well as a direct connection between the top of the device and the chassis (if the chassis is metal or another good thermal conductor), in which case the chassis becomes a heat sink. When applied to the top of a package, heat sinks increase the effective surface area of the package face, increasing convection and radiation off of the top surface of the package.

Typically, without a heat sink, 80-90% of the heat generated by the device is dissipated through the PCB. Attaching a heat sink improves the heat flow through the top of the device. A good heat sink could increase the percentage of heat flowing through the top of device from 10-20% up to 30-80%, resulting in the following improvements:

- Estimated reduction in $\theta_{JA, \text{effective}}$ of 20-80%
- Estimated T_{Junction} reduction of 10-30 °C

You must perform detailed analyses to determine the exact impact of a particular heat sink in a certain system.

8 Heat Sink Recommendations

There are several general types of heat sinks available in the market for cooling BGA IC devices such as the DM64xx, DM64x, and C6000 devices. The simplest approach is to find a standard product from a heat sink supplier. There are often options for significant optimization of the heat sink type and design based on the details of the application (geometry, usage, chassis material, design flexibility, assembly flow, etc.), which can result in better thermal performance, and usually a more cost-effective design as well. This section describes examples of simple, mid-range, and higher-performance heat sink types, as well as recommendations on heat sink selection and a list of potential heat sink vendors.

The simplest type of heat sink is a spreading plate that is attached to the top of the device, such as <http://www.chomerics.com/products/twing.htm>.

Most standard heat sinks are of the plate-fin or pin-fin type, where the heat sink has a base and fins that extend off the base. These fins can be rectangular or round and extend at different angles and profiles. There types of heat sinks are readily available at fairly reasonable prices, but the key to selecting this type of heat sink is to look at the airflow regime. For example, if forced airflow is coming from one direction, a design with long rectangular fins may be optimal, but if forced airflow is mixing a lot, then round fins may be needed to ensure air effectively moves through the fins. If there is no forced airflow, it is important to consider the heat sink performance curve with natural convection (often called θ_n), as performance might be worse than with forced airflow. An example of this type of heat sink (used for calculations in the previous section) is available here: <http://www.aavidthermalloy.com>.

A radial type heat sink, where there is a round plate which attaches to a pedestal that presses on to the top of the part, may provide a better performance in some applications. This type features much lower thermal resistance values at natural convection, as seen in the following example: <http://catalog.tycoelectronics.com>

As the industry trends towards miniaturization and increased power density, many heat sink vendors are already advertising that they support custom designs with quick prototypes and flexible manufacturing.

Based on the number of heat sink types available (standard and custom) and the uniqueness of the applications, TI recommends that if thermal analysis indicates the need for a heat sink in a customer's application, the customer should work closely with a heat sink vendor to find an optimal solution that meets the thermal needs as well as other system design constraints.

9 Heat Sink Attachment Methods

When attaching a heat sink to a package surface, it is important to reduce the thermal resistance of the heat sink attachment. If you use a thermal insulating material between the heat sink and the package surface, the thermal performance could be worse than having no heat sink at all. Calculate the thermal resistance of the bond line layer as follows:

$$\theta_{ca} = \frac{t}{kA}$$

Where:

- t = Heat sink compound bond line thickness
- k = Thermal compound conductivity
- A = Package surface area

Three primary materials are commonly used to attach heat sinks to the package: epoxy glue, thermal grease, and thermal pads with and without self adhesive. Other thermal interface materials include Grafoil® and solders.

9.1 Epoxy Glue

The most reliable material for attaching a heat sink is a thermally conductive epoxy compound. These materials can be purchased from heat sink vendors, and have thermal conductivities that typically range from 0.5-1.5 W/m-°C. There are also specialty materials with metal fillers that have much higher bulk thermal conductivities. When gluing the heat sink to the package surface with an epoxy, use pressure during the cure process to squeeze out excess material and minimize the bond line thickness. When a heat sink is attached with an epoxy, it is important to clean the package surface of any greases or contaminants that can degrade the adhesion strength. The adhesive/package combination should be tested in the intended environment to ensure reliable operation over the lifetime of the device.

The advantages of epoxies in attaching a heat sink include:

- No fixturing is required to hold the heat sink in place after the epoxy has cured
- The epoxy can fill large surface asperities.
- There is little or no change in thermal properties as a function of time and temperature
- Good shock and vibration resistance.

The disadvantages include:

- The epoxy attach is usually permanent, meaning the heat sink cannot be removed from the package if necessary
- Fixturing may be required to hold the heat sink in place with pressure during epoxy cure. This can increase the cost of the heat sink assembly substantially.
- Epoxies may not adhere strongly to certain plastic compounds such as those used in plastic molded IC packages.

9.2 Thermal Greases

Thermal greases have long been used to minimize the thermal contact resistance between a heat sink and package surface. These materials are normally formed by suffusing high viscosity silicone greases with metal oxide powders for thermal conductivity. Thermal conductivities are roughly 0.6-0.9 W/m-°C.

Advantages include:

- Easy to apply
- Allows heat sink removal
- Good gap filler for non-planar surfaces

Disadvantages include:

- Heat sink needs to be clamped to package with some force to minimize the bond line thickness
- Silicone has a tendency to wet out over other surfaces, depleting the grease and making it brittle over time, which reduces the thermal conductivity
- Can be messy to apply

9.3 Thermal Pads

Thermal pads, with or without pressure sensitive adhesives, are often used to attach large heat sinks to packages. Thermal pads normally consist of low modulus (pliable, rubbery) polymer material that is filled with a thermally conductive material. Thermal conductivities range from 0.8-3 W/m-°C. They have multiple advantages over epoxies or greases, but also some disadvantages.

Advantages:

- Easily handled
- Can be cut to fit
- Can easily remove the heat sink
- Little performance change with time

Disadvantages include:

- Must have method to clamp heat sink to package surface
- Not as good as epoxy or grease at filling between warped surfaces
- Normally, the bond line achievable with these materials is thicker than can be achieved with epoxies or thermal greases

Many adhesives used on thermal pad materials are pressure sensitive, and non-permanent. As such, they may be sensitive to changes in moisture in the environment and tend to creep under loading. If the system is positioned such that there is substantial gravitational loading of the heat sink on the package; i.e., the PCBs are positioned vertically such that the heat sinks are pulling on the package, pressure sensitive adhesives alone should not be relied upon to hold the heat sink to the package.

10 Heat Sink Vendor List

Here is a list of a number of potential heat sink vendors:

- Aavid Thermalloy: <http://www.aavidthermalloy.com/products/bga/index.shtml>
- Alpha: <http://www.alphanovatech.com/>
- Calgreg: <http://www.calgreg.com/heatsinks.html>
- Chomerics: <http://www.chomerics.com/products/thermal.htm>
- Enertron: <http://www.enertron-inc.com/enertron-products/index.php>
- Graftech: <http://www.graftechaet.com/Home/Brands/eGRAF.aspx>
- Malico: <http://www.malico.com.tw/>
- Radian: <http://www.radianheatsinks.com/>
- R-Theta: <http://www.r-theta.com/>
- ThermShield: <http://www.thermshield.com/ThermshieldPages/ThermalProducts.html>
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