Abstract/Purpose/Benefit

This document has been compiled to provide specific information and considerations regarding thermal design requirements for all Keystone DSP processors. The information contained within this document is intended to provide a minimum level of understanding with regards to the thermal requirements and thermal management necessary to assure proper operation of the DSP processor. Failure to establish and maintain the minimum requirements identified within this document (and related data sheet) can reduce the life, reliability, or performance of the DSP. Under certain conditions, exceeding the thermal requirement can permanently damage the DSP. In all cases, if the thermal requirements identified in this document and the respective data sheets are not met, any warranty - implied or otherwise stated - will be null and void.

Contents

1 Introduction ............................................................. 3
2 Thermal Metrics ......................................................... 3
   2.1 $\theta_{ja}$ (Theta-ja) ................................................. 3
   2.2 $\theta_{jb}$ (Theta-jb) ................................................ 3
   2.3 $\theta_{jc}$ (Theta-jc) ................................................ 4
   2.4 $\theta_{jma}$ (Theta-jma) ............................................. 4
   2.5 $\psi_{jb}$ (Psi-jb) ................................................... 4
   2.6 $\psi_{jt}$ (Psi-jt) ..................................................... 4
   2.7 $\theta_{ca}$ (Theta-ca) ............................................... 4
   2.8 $\theta_{cs}$ (Theta-cs) ................................................ 4
   2.9 $\theta_{sa}$ (Theta-sa) ............................................... 5
3 Thermal Models .......................................................... 6
   3.1 1R Model ........................................................... 6
   3.2 2R Model ........................................................... 6
   3.3 3R Model ........................................................... 7
   3.4 4R Compact Model ............................................... 7
   3.5 Star Shaped Resistor Model ..................................... 8
   3.6 $\theta_{jb}$ - Theta-jb System Model ................................. 8
   3.7 Delphi Compact Network Thermal Resistor Model .......... 8
4 Tools ................................................................. 11
   4.1 Network Calculators ............................................. 11
   4.2 Three Dimensional Modeling and Simulators ................. 11

Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this document.
List of Figures

Figure 1  Common 1R Thermal Resistance Models ........................................... 6
Figure 2  2R Thermal Resistance Models .......................................................... 7
Figure 3  3R Thermal Resistance Model ............................................................ 7
Figure 4  4R Compact Resistor Thermal Model .................................................... 7
Figure 5  4R - Star Shaped Thermal Resistor Model .......................................... 8
Figure 6  Theta-JB System Model ................................................................. 8
Figure 7  Delphi Compact Thermal Model ........................................................ 9
Figure 8  Current (preliminary) TI Delphi Model .............................................. 10
Figure 9  DSP to PCB Thermal Paths ............................................................... 18
Figure 10 Trace Length vs Trace Width - Pwr Dissipation .................................. 19

List of Tables

Table 1 Multiplication Factor. ........................................................................... 12
Table 2 Thermal Coefficient of Common Materials ........................................... 20
1 Introduction

The DSP(s) and application (system) reliability, as well as electrical functionality and performance, is in part determined by the operating temperature under which all logic functions. As process nodes continue to shrink, processors become more complex and power increases the control of variables such as component temperatures has become more critical to successful designs. Complex and more accurate calculations are performed using common CFD (computational Fluid Dynamic) tools are strongly recommended by Texas Instruments, especially for complex systems.

2 Thermal Metrics

Many thermal metrics exist for the IC processors (DSP), these range from $\theta_{ja}$ (Theta-ja) to $\Psi_j$ (Psi-jt). Each of these is commonly and frequently misapplied by end users in an attempt to estimate the critical DSP (IC) junction temperature within an application system. To effectively use these metrics, it is necessary to understand the variables affected by each of them and how variables relate to results and assumptions. Each is ultimately used in conjunction with $\theta_{jc}$ (Theta-jc) or junction to case thermal resistance to obtain a typical thermal model.

2.1 $\theta_{ja}$ (Theta-ja)

Theta-ja or junction to ambient thermal resistance is the most widely used (and misused) thermal metric. $\theta_{ja}$ is actually the measure of the thermal performance of the DSP package that has been mounted on a specific test board (as defined within JEDEC JESD51). Theta-ja is actually a metric designed to establish a base line for comparison of relative thermal performances of IC packages.

Historically the equation $T_{junction} = T_{ambient} + (\theta_{ja} \times \text{power})$ has been used to estimate IC (DSP) junction temperatures in still air. Although this does result in an approximate value it is in no way accurate enough for today's high performance DSP processors. The model accuracy is based on the $\theta_{ja}$ thermal parameter which is a function of more than the package, including other variables including PCB design and layout, material, ambient conditions, and system topology. In essence, the systems application board (PCB) is a heat sink that the BGA solder balls are mounted to. Variation in PCB designs, DSP pad layout, and topology change the efficiency of the heat sink. Utilizing a predefined test set up (per JEDEC for measuring $\theta_{ja}$) results indicate that 70-95% of the total power generated by the chip is typically dissipated to the systems application board and not from the package surface (this assumes still air and no heat sink). Variables (in decreasing order of magnitude affecting theta-ja measurements include: PCB design, BGA solder ball or pad size, Internal package design (substrate and die layout), system physical altitude, external ambient temperature, and power dissipation. Theta-ja ($\theta_{ja}$) is typically composed as a sum of two thermal resistances; Theta-jc ($\theta_{jc}$) and Theta-ca ($\theta_{ca}$).

2.2 $\theta_{jb}$ (Theta-jb)

Theta-jb or junction to board thermal resistance (also referred to as junction-to-pin thermal resistance), represent the thermal resistance between the package and the system application board (PCB) with a single number. Theta-jb is intended to establish and provide a first approximation of the DSP’s thermal junction temperature. Although theta-jb is a single value, there are actually multiple distributed thermal paths (through solder balls and package) to the PCB and ambient surroundings. Theta-jb ($\theta_{jb}$) is based on a simple 3 resistor thermal approximation. Refer to the thermal model section for relative figures.
2.3 \( \theta_{jc} \) (Theta-jc)

Theta-jc (\( \theta_{jc} \)) is still a common metric used in applications where the DSP or IC package includes a heat sink. The \( \theta_{jc} \) (junction-to-case thermal resistance) metric was originally devised to estimate the thermal performance of a package when a heat sink was attached. Theta-jc for all intentions is no longer suitable for proper DSP BGA package thermal analysis. Recent technologies have significantly improved junction to case thermal transfers, more and more DSPs now have packaging materials or lids that increase thermal transfer through the package to the environment. Along with improved packaging materials and die (and substrate) layout, conduction, convection, or radiated power in the form of heat is more efficiently transferred. To replace the theta-jc metric, \( \Psi_{jt} \) or Psi-jt has been developed and should be utilized when no heat sink applied.

2.4 \( \theta_{jma} \) (Theta-jma)

Theta-jma is identical to Theta-ja with one exception, \( \theta_{jma} \) takes into account the effect of a forced convection between the junction and moving air. In the case of Theta-jma, the findings are presented as a function of air movement velocity (movement).

2.5 \( \Psi_{jb} \) (Psi-jb)

Psi-jb (\( \Psi_{jb} \)) is the latest in thermal metrics used to more accurately estimate in-use junction temperatures from a measured board temperature. The following represents the equation most frequently used:

\[
T_{\text{JUNCTION}} = T_{\text{BOARD}} + (\Psi_{jt} \times \text{Power})
\]

2.6 \( \Psi_{jt} \) (Psi-jt)

Psi-jt (\( \Psi_{jt} \)) [and Psi-jb] is the latest in thermal metrics used to more accurately estimate in-use junction temperatures from a measured case temperature (when a heat sink is not used). This metric is defined differently (Psi [\( \Psi \]) character as opposed to Theta [\( \theta \)] character) since \( \Psi_{jt} \) is not a true thermal resistance. The following represents the equation most frequently used.

\[
T_{\text{JUNCTION}} = T_{\text{CASE}} + (\Psi_{jt} \times \text{Power})
\]

2.7 \( \theta_{ca} \) (Theta-ca)

Theta-ca or case to ambient thermal resistance was originally developed as a metric for metal packages with a constant case temperature and that were not thermally coupled to the systems board (PCB).

2.8 \( \theta_{cs} \) (Theta-cs)

Theta-cs or case to heat sink thermal resistance can be approximated using the following formula:

\[
\theta_{cs} = \frac{T}{(k \times A)}
\]

Where:
- \( T \) = The thickness of interface layer between package and heat sink
- \( k \) = The bulk thermal conductivity of the thermal interface material
- \( A \) = The area over which the thermal interface material is applied

This is only an estimate since the thermal interfacial resistance that develops between any two surfaces is neglected. It is however recommended to increase the accuracy of the model in use so that this value is measured across use case extremes.
2.9 $\theta_{sa}$ (Theta-sa)

Theta-sa or heat sink to ambient thermal resistance
3 Thermal Models

Thermal models come in various configurations. Model selection depends on selection criteria and can be limited by the tools available. Models range from a simple 1R (one resistor) model to a more complex multi-resistor model commonly referred to as a network compact or Delphi model. As model complexity increases towards the network compact model, it is typically assumed that the performance and accuracy of the model also increases.

The following section provides a general overview of typical thermal models, the models are provided in increasing levels of complexity. Although Texas Instruments recommends and intends to provide Network Compact Thermal models (Delphi) for all KeyStone DSPs and beyond, it is important to understand the relationship and complexities of other common models, especially when constructing a system level simulation model.

3.1 1R Model

A 1-R (1R or one resistor) model typically represent a single transition point usually originating from the junction (transistor junction). 1R models are used to build more complex models described below. Examples of basic 1R models include:

- Theta-ja (junction to ambient thermal resistance)
- Theta-jb (junction to base {or board/PCB} thermal resistance)
- Theta-jc (junction to case thermal resistance)

Additional 1R models also include:

- Theta-ca (case to ambient thermal resistance)
- Theta-cs (case to heat sink thermal resistance)
- Theta-sa (heat sink to ambient thermal resistance)

The following model (Figure 1) is provided as a graphical representation for common 1R thermal models.

**Figure 1 Common 1R Thermal Resistance Models**

3.2 2R Model

A 2-R (2R or two resistor) model typically incorporates a junction point with two accompanying end points as illustrated in Figure 2. In some cases a 2R model may not include the transistor junction point; this construction typically is reserved for independent analysis of case and or heat sink constructions. For use with the DSP and throughout the remainder of this document, a 2R model will refer incorporate a junction point. A 2R model is considered to be a basic model when performing a first approximation thermal analysis.
3.3 3R Model

A 3-R (3R or three resistor) model incorporates a junction point, one intermediate and two end points as illustrated below. A 3R model is more accurate than a 1R or 2R model by allowing for additional thermal gradients or variables to come into play.

Figure 3 is provided as a graphical representation for common 3R thermal models.

3.4 4R Compact Model

A 4-R (4R or four resistor) compact model (Figure 4) was designed to provide even greater accuracy then the previously discussed models.
3.5 Star Shaped Resistor Model

A Star Shaped resistor model was designed to improve upon the accuracy of the previously identified models. During thermal characterization, especially when using the common Bar-Cohen method, a star shaped thermal resistance model is used. As noted in Figure 5, the star shaped thermal resistance model contains a junction point with four equivalent thermal resistors radiated from the junction center point.

![Figure 5 - 4R - Star Shaped Thermal Resistor Model](image)

3.6 $\theta_{JB}$ - Theta-jb System Model

Figure 6 illustrates a simple theta-jb systems simulation model. All thermal resistances denoted within the PCB account for variations in board material, topologies, traces, thermal vias, and the like. Combined, these allow for an approximate calculation of the DSP junction temperatures.

![Figure 6 - Theta-JB System Model](image)

3.7 Delphi Compact Network Thermal Resistor Model

Unlike many of the previous models, most network compact models like the Delphi model are mathematical constructs, and not thermal resistances. A Delphi or compact model does not correspond to a specific physical thermal resistance between the two nodes. All Delphi models are designed around vendor (Texas Instruments) internal analysis. The Delphi model is designed to be used with common resistor network solvers, CFD tools, and other system level thermal simulation tools. The Delphi compact model is typically the best representative mode for the DSP and typically includes a representation of all the heat conduction paths.
Delphi compact models are what Texas Instruments intends to offer in support of the DSP thermal analysis. With this in mind understanding Delphi models and inherent constraints is necessary. All surface nodes on the Delphi model are by definition associated with only one temperature. Lastly, the Delphi models offered by Texas Instruments will closely approximate the effect on the environment of the actual package.

Figure 7 is provided as a graphical representation for a common DSP Delphi thermal resistance model.

Figure 8 is the current representation of a TI model for a KeyStone DSP. This model is representative of only one DSP; refer to your specific thermal model for actual thermal resistive values. The Delphi model as illustrated in Figure 7 denotes a full packaged or encapsulated model whereas the Delphi model illustrated in Figure 8 represents a lid attached construction as used by Texas Instruments.
Figure 8  Current (preliminary) TI Delphi Model

Heat Transfer to Heatsink or Air

Top Inner

Junction

Bottom Inner

Package Side

8.397470 e+000

1.5386

17e+

2

6.903620 e+000

5.676049 e+01

1.800000 e-001

1.83996e-001

1.83996e-001

1.83996e-001

Bottom Outer

Heat Transfer To PCB
4 Tools

There are two basic classifications of thermal modeling tools, each with their own set of limitations and benefits. These include:

- Network calculator tools
- Three dimensional modeling tools.

4.1 Network Calculators

A network calculator tool uses resistors as network links to develop the entire system. Surface or Top nodes are connected to appropriate nodes within the environment. This is defined in greater detail in the JEDEC Standard, JESD15-3 (Two-Resistor Compact Thermal Model Guideline). A network calculator (as with all tools discussed) require the "User" to properly and correctly determine and implement variable factors including environmental conditions and heat capacity of the ambient air to the top node of the model.

4.2 Three Dimensional Modeling and Simulators

The second class of tools is referred to as 3-D modelers. This class is generally defined by both CFD (Computational fluid dynamics) and CM (Conduction Modeling or non-CFD) tools. Other tools within this class do exist but are not as widely used. This group of tools focuses on heat transfer based on equations in a 3-D field using differential equations. Models used within these tools include the Texas Instruments recommended Delphi compact thermal resistance model which is also further defined in JESD15-4.

Conduction modeling tools are used to solve defining equations for conduction heat transfer within the solid portions of the system. Airflow effects are solved indirectly; they are applied as an equivalent heat transfer coefficient to the solid air (exposed) interfaces of the model (top and sides). Any surface (of the model) in contact with the system board (PCB) and / or heat sink are managed within the conduction heat transfer calculation.

Computational fluid dynamics (CFD) tools work to solve both the air and solid portions of the system directly. Heat transfer and fluid flow calculations are based on the Navier-Stokes equations for the exposed sides. As with the conduction modeling tools, any node in contact a solid utilizes the conduction heat transfer equations and calculations to derive a result. Most all quality CFD tools support transfer analysis for radiation, conduction, and convection of heat. CFD tools, although typically more precise require correct physical geometries for discrete devices and systems to be accurate.
5 Thermal Variables

Multiple variables directly affect proper thermal measurements and calculations which need to be considered. The following sections discuss several of the independent factors to also consider.

5.1 Ambient Temperatures

Theta-ja changes with respect to ambient (internal operating temperatures) temperature changes. This is due to density, viscosity, and heat capacity of the ambient air. Prior internal thermal analysis resulted in an approximately a 10-20% improvement in the $\theta_{ja}$ when it was measured against an ambient of 0-100°C, which was an improvement of approximately 20% over the $\theta_{ja}$ when measured at a 0°C ambient temperature.

5.2 Power Dissipation

DSP package design also affects the convection, conduction, or radiated energy loss from the BGA package. In general, the higher the temperature on the BGA package surface gets, the more efficient convection, conduction, and radiation heat loss to the ambient environment becomes. As the package power rating increases, the theta-ja also improves.

5.3 Altitude

Altitude of the end product can have a significant effect on theta-ja measurements. External ambient temperatures differ at varying altitudes due to the cooling efficiency capability and static air pressure. The higher the altitude the higher expected temperature of a like application running under identical conditions. Prior research conducted (by IBM) resulted in a de-rating factor to be applied when operating at various altitudes. The following altitude and multiplication factors (Table 1) should also be taken into consideration when operating at various elevations.

<table>
<thead>
<tr>
<th>Altitude (ft/m)</th>
<th>Multiplication Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (0)</td>
<td>1.0</td>
</tr>
<tr>
<td>3000 (914.4)</td>
<td>1.1</td>
</tr>
<tr>
<td>5000 (1524)</td>
<td>1.14</td>
</tr>
<tr>
<td>7000 (2133.6)</td>
<td>1.17</td>
</tr>
<tr>
<td>8350 (2545.08)</td>
<td>1.2</td>
</tr>
</tbody>
</table>

5.4 Environmental Conditions

External to the system is an environment, that environment depending on its ability to exchange heat originating on the DSP and system application can dramatically impact the overall performance. Care should be taken to design the system for the intended environmental conditions.
5.5 System PCB Design

PCB design can have a large impact on DSP thermal management. Design topologies that place complementary components in close proximity to the DSP can also contribute to higher junction temperatures. The ability of the DSP to properly dissipate power (in the form of heat) through the PCB and into the environment as well as through the lid utilizing conduction or convection methods is critical to all designs. Refer to Section 7 for additional detailed information regarding PCB design recommendations.

5.6 DSP Cooling

The DSP can be cooled using one of three common methods:

- conduction
- convection and/or
- radiation

Radiation is the simplest and typically the least effective. A DSP resting in place will naturally radiate heat into the environment (assuming the environment is a lower temperature than the DSP) until such a time thermal equilibrium is obtained. Radiation as defined and used in this document is the natural radiation or transfer of heat from the DSP to the ambient environment. This differs slightly when applying conduction or convection techniques.

Conduction, unlike radiation utilizes an interconnecting object (heat sink, thermal posts, thermal conductive material, etc) to conduct heat away from the DSP. The most commonly used conduction method is a heat sink. Heat sinks vary in size, construction and attach methods - each will play a large role in defining how well a conduction method works. A heat sink applied directly to the individual DSP may not be adequate enough to transfer the necessary amount of heat away. Limiting factors when using strictly conduction include ambient temperature, thermal attach material, number and size of heat sink fins. Other common methods of thermal conduction used within DSP applications include lid attach and thermally conductive (electrically insulated) materials. Lid attach typically implies an extruded or molded lid to an application that directly comes in contact with the DSP and draws heat away from the DSP to the external ambient environment. This method typically works well but has several design limitations that must be considered. In a lid attach configuration the thermally conductive lid (usually either a molded compound extruded aluminum with fins to radiate heat away), depending on tolerances and PCB planarities can crush the DSP, possibly damaging it permanently. Dissimilar materials have different rates of expansion and contraction - also adding to the potential risk. In a lid attach design, an electrically isolated thermally conductive elastomer is recommended between the DSP and conductive source. This same elastomeric material can be used between the DSP and the standard thermally conductive lid (non-extruded) but will yield far worse results than a direct coupled (with a small thermal pad) lid attach method.

Convection, on the other hand, typically produces the best results. Proper design of the PCB such that forced air is allowed to freely move over the DSPs generally produces the most optimum results. In a convection designed cooling system, the amount of air flow (cfm or cubic feet per minute), internal and external ambient temperatures, and static pressure play a large role in determining the junction temperature of the DSP. When designing a convection cooling system CFD tools should always be used to determine the optimum design and placement of components. A suitable plenum for air to move with little resistance over the DSPs provides the best efficiency in a design. Size and
number of fans will also have an impact on thermal performance. For designs intended for inside applications, the fan(s) pitch, cfm, and number of blades should be evaluated against the thermal cooling criteria. Too fast of a cfm fan will result in good air flow, but typically be load. Too small of a fan (or fan blades) and not enough air movement will be realized.

To some degree conduction and radiation are always present in a design, power in the form of heat is conducted away from the DSP into the board, and the power or heat within the PCB or DSP is naturally radiated into the surrounding environment. The best solution (in an ideal configuration) is a combination of all three methods.
6 Thermal Equations

The following is a summary of equations used to approximate relative junction temperatures of the DSP.

6.1 $\theta_{JA}$

$\theta_{JA} = \theta_{JC} + \theta_{CA}$: Theta-JA thermal resistance calculation

$\theta_{ja}$ or Theta-JA (Junction to Ambient) is the package thermal performance based on the sum of two coupled resistances, $\theta_{jc}$ and $\theta_{ca}$.

6.2 $\theta_{JMA}$

$\theta_{JMA} = \theta_{JC} + \theta_{CA}$: Theta-JMA thermal resistance calculation

$\theta_{jma}$ or Theta-JMA (Junction to Ambient) is the package thermal performance based on the sum of two coupled resistances, $\theta_{jc}$ and $\theta_{ca}$ with forced air movement (velocity) per the JEDEC standard.

6.3 $\theta_{JC}$ - Original Junction Temperature

$T_{\text{JUNCTION}} = T_{\text{CASE}} + (\theta_{JC} \times \text{Power})$: Junction Temperature Calculation

This calculation represents the original equation used, however this is not recommended as the majority of the power is conducted, convected, and radiated off the PCB to which the DSP package is attached.

6.4 $\theta_{JC}$ – Improved Junction Temperature with Heat Sink

$T_{\text{JUNCTION}} = T_{\text{AMBIENT}} + ((\theta_{JC} + \theta_{CS} + \theta_{SA}) \times \text{Power})$: Junction Temperature - Simple System Calculation with Heat Sink

This calculation represents the preferred equation to be used when performing simple calculations on junction temperatures where a heat sink exists. This equation is recommended and most accurate for packages where $\theta_{jc}$ is small compared to $\theta_{ja}$. In other words this equation is recommended for DSP applications where the majority of the heat can be dissipated through the lid of the package when an efficient heat sink is utilized.

6.5 $\theta_{JC}$ – Improved Junction Temperature with Heat Sink – Complex Systems

$T_{\text{JUNCTION}} = T_{\text{AMBIENT}} + (\theta_{JA} \times (\theta_{JC} + \theta_{CS} + \theta_{SA}) / (\theta_{JA} + \theta_{JC} + \theta_{CS} + \theta_{SA})) \times \text{Power}$: Junction Temperature - Complex System Calculations with Heat Sinks

This equation is recommended over the previous equation when calculating approximate junction temperatures in cases where greater accuracy is required.

6.6 $R_T$

$R_T = T_{\Delta} / W$: Solid Thermal Resistance
6 Thermal Equations

Used to calculate the thermal resistance of a solid material; in this case a DSP package. Results are typically expressed as °C/W. The following is offered as an example where:

\[ W = 10 \]
\[ \Delta T = 3 \, (^\circ C) \]
\[ R_T = \frac{3}{10} \]

6.7 \( \Psi_{jt} \)

\[ T_{ Junction } = T_{ Case } + (\Psi_{jt} \times Power) \text{: Calculated Thermal Resistance Model} \]

Psi JT or \( \Psi_{JT} \) is the thermal characterization parameter between junction to top. Top (or \( T_{TOP} \)) is the temperature at the top center of the package. The term power refers to total heat dissipated from the DSP through any thermal path and not just the lid or case. The following equation can also be substituted when using the Psi-JT method:

\[ \Psi_{JT} = \frac{T_{J} - T_{TOP}}{Power} \]

6.8 \( \Psi_{jb} \)

\[ T_{ Junction } = T_{ Board } + (\Psi_{jb} \times Power) \text{: Calculated Thermal Resistance Model} \]

Psi JB or \( \Psi_{JB} \) is the thermal characterization parameter between junction to board. Board refers to the temperature at the bottom center of the mounting surface. The term power refers to total heat dissipated from the DSP through any thermal path and not just the lid or case. The following equation can also be substituted when using the Psi-JT method:

\[ \Psi_{JB} = \frac{T_{J} - T_{BOARD}}{Power} \]
7 PCB Thermal Design Considerations

DSP(s) and application (system) reliability, as well as electrical functionality and performance, is in part determined by the operating temperature under which all logic functions. As process nodes continue to shrink, processors become more complex and power increases the control of variables such as component temperatures has become more critical to successful designs.

Independent variables (factors) that can be controlled and impact the DSP temperature include operating power, surrounding air flow, heat sources (peripheral components), orientation, internal and external system ambient temperatures, layout topologies and assembly board material (PCB or PWB). Printed circuit board design factors would include the width and thickness of the copper (Cu) trace contacting each of the component pins (balls, legs, pad etc), the number and area of copper planes that connected to each, thermal vias that may be designed between them and the spreading planes, and the proximity of other components or heat generating sources.

Proper thermal design to control DSP temperatures require consideration and implementation of factors that promote energy flow. It is impossible to reduce the requirements for proper thermal management to a single formula given all the possible variables and design permutations. The complex interactions between constraints and variables requires application level software programs and 3-D models to be constructed in order to get to a first order approximation. Historically, a simple thermal equation was used to calculate component temperatures from a common thermal resistor model referred to as a Theta-ja ($\Theta_{ja}$) model.

$$T_{\text{junction}} = T_{\text{ambient}} + (\Theta_{ja} \cdot \text{Power})$$

Where:
- $T_{\text{junction}}$ = temperature of the active portion of the component
- $T_{\text{ambient}}$ = temperature of the air at the specific component location
- $T_{\text{junction}}$ = temperature of the active portion of the component
- $\Theta_{ja}$ = thermal resistance of the component (DSP) as defined by JEDEC
- Power = power of the DSP

JEDEC (Joint Electron Device Engineering Council) states that for $\Theta_{ja}$, $\Theta_{ja}$ is not a constant. It is therefore a function of the printed circuit board to which it is applied (soldered down to) and can vary by a factor of two or more depending on the PWB design layout. Therefore, if component temperatures are calculated using the above equations; erroneous estimates may be obtained which would possibly lead to a application or system design that can fail thermally.

7.1 PCB Material Used as a Heat Sink

The printed circuit board or PCB can be thought of as a heat sink to which is soldered the individual DSP balls or the legs (leads). The PCB, and the design and layout of your PCB, can significantly impact its efficiency as a heat sink. Figure 9 illustrates a typical application whereby a DSP is mounted (on the top of the PCB and connected via solder balls, and on the bottom via soldered legs) on the PCB. This figure illustrates how heat is generated and transferred from the DSP to the PCB. Conversely heat can travel from the PCB to the DSP depending on where the larger thermal mass lies. Heat is generated as current flows through electrical resistances on the active surface of the DSP die. A thermal gradient is established as the surface temperature rises. Heat in the form of thermal energy migrates from areas of higher temperature to areas of lower temperatures. In the following figure higher temperatures from either of the DSP dies would transfer to the PCB. In the event the PCB (or surrounding components) were
higher in temperature, the thermal transfer would be between the PCB to the DSP. In a typical configuration (where the DSP is the highest temperature), heat would flow from the DSP die through the bumps (die attach), then through the copper metal substrate (in the package), through the solder balls (solder joints connecting the BGA package to the PCB). In a proper thermal designed PCB, thermal conduction would occur between the BGA solder balls (or legs if applicable) onto the PCB and spread out over the entire area of the PCB thus allowing for a potentially efficient form of convection, conduction, and radiation into the environment. Design of the PCB with minimal heat transfer paths will insulate the DSP resulting in an increase in DSP temperature.

**Figure 9**  
**DSP to PCB Thermal Paths**

Proper design of the PCB is paramount to good thermal management of the application system. As PCB system designs vary, it is estimated that as much as 95%\(^1\) of thermal energy can be dissipated by the PCB. Obtaining such thermal (transfer) performance can be achieved by following strict requirements, including but not limited to the following:

- Large spreading planes (conduct heat away from the DSP and components)
- Sparsely populated PCBs with large areas for convection & radiation (not typically possible)
- Long\(^2\) traces interconnecting the components, again to conduct heat away from the components (Practical within reason)
- Sufficient spacing of PCBs in a system rack to enable adequate convection

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**Note**—\(^1\): From PCB Design for Thermal Performance

**Note**—\(^2\): Long traces should be used where not constrained by other routing requirements.
A proper understanding of the thermal characteristics of the KeyStone DSP is critical for proper design of the application board and system. The maximum case temperature of the device must not be exceeded which requires adequate heat dispersion through a heat sink (or alternate sufficient cooling) to be a part of the thermal design. Refer to the data sheet for acceptable operating temperature ranges. Exceeding the recommended operating temperatures will decrease the DSP reliability and may cause premature failure. Additionally, operating outside the recommended operating ranges may have an effect on timing and performance.

### 7.2 Trace Layout and Considerations

When considering trace layout for signal integrity it is also important to take into account power rating and thermal or power dissipation (in Watts). The following figure provides the relative power dissipation for various trace widths (in inches) as compared to trace lengths (in inches). For this example, a 1 oz., 62.5 mil FR4 PCB was selected with a 25°C ambient temperature and a 50°C temperature rise. The information is provided to illustrate the advantages of wider traces when connecting to the solder balls (pins) of the DSP.

Examining the results for a 2" trace, 10 mils in width, calculates to approximately 0.50171W dissipated through/over the trace whereas the same length trace but only 4 mils in width calculates to only dissipate approximately 0.33218W (33.8% lower power dissipation with the narrower trace).

Further examination for a 0.5" trace, 10 mils in width, calculates to approximately 0.12543W dissipated through/over the trace whereas a 0.5" trace 4 mils in width calculates to only dissipate approximately 0.08305W (33.8% lower power dissipation with the narrower trace).

![Figure 10 Trace Length vs Trace Width - Pwr Dissipation](image-url)
7 PCB Thermal Design Considerations

Where possible it is recommended that added copper be laid for traces and especially power pads for relative power supplies as recommended in each respective data sheet. As a further example, a 1.5” × 1.5” 1oz. copper pad under a device (and directly coupled) is theoretically capable of dissipating 1.03743 watts.

7.2.1 PCB Size

PCB size has an impact on the thermal design of the end system, unfortunately most industries have predefined application form factors that must be followed. Inherently a larger PCB relates to more mass (copper) thus resulting in better heat dissipation. For academic purposes we shall state that a larger PCB will improve the overall thermal characteristics (this assuming good engineering design practices are applied.

7.3 Heat Transfer

There exist several methods for meeting the thermal requirements of the DSP, the two most common methods are conduction and convection.

7.3.1 Conduction

Conduction heat transfer refers to the conduction or direct contact between two surfaces resulting in a thermal transfer from one surface (higher temperature) to another (lower temperature). When referring to the cooling of the DSP in an application/system this usually involves the direct contact of a heat sink (attached or possibly part of the system enclosure. The thermal heat generated by the DSP is transferred to an attached heat sink/outer enclosure thereby reducing the heat (conducting it away) on the DSP. In all conduction methods, the material used, compression forces, and ambient temperatures affect the transfer rates. Table 2 defines various material used today and the relative thermal coefficients of each.

Table 2 Thermal Coefficient of Common Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity W / mK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.026</td>
</tr>
<tr>
<td>Aramide / Epoxy</td>
<td>0.20 - 0.30</td>
</tr>
<tr>
<td>Thermal Grease</td>
<td>0.20 - 0.70</td>
</tr>
<tr>
<td>Polyimide / E Glass</td>
<td>0.2 - 0.4</td>
</tr>
<tr>
<td>E-Glass Fiber</td>
<td>0.3 - 0.4</td>
</tr>
<tr>
<td>FR4 / E Glass</td>
<td>0.3 - 0.4</td>
</tr>
<tr>
<td>PTFE Ceramic (RO3000)</td>
<td>0.5 - 0.66</td>
</tr>
<tr>
<td>Thermal transfer tape</td>
<td>0.6</td>
</tr>
<tr>
<td>Non PTFE Ceramic (RO4000)</td>
<td>0.6 - 0.65</td>
</tr>
<tr>
<td>Thermally Conductive Silicon Pad</td>
<td>1.6</td>
</tr>
<tr>
<td>Thermally Conductive Elastomer</td>
<td>1.1 - 1.9</td>
</tr>
<tr>
<td>Doped Thermal Grease</td>
<td>1.68 - 2.58</td>
</tr>
<tr>
<td>Thermally Conductive Acrylic Pad</td>
<td>2.0 - 3.0</td>
</tr>
<tr>
<td>Soft Thermally Conductive Silicon Pad</td>
<td>3.1</td>
</tr>
<tr>
<td>Thermally Conductive Silicon/Ceramic Pad</td>
<td>1.0 - 4.1</td>
</tr>
<tr>
<td>Natural Graphite Thermal Pad</td>
<td>6 - 10</td>
</tr>
<tr>
<td>Low Modulus Carbon Fiber</td>
<td>8 - 12</td>
</tr>
<tr>
<td>Natural Graphite Thermal Pad + Polymer</td>
<td>16</td>
</tr>
<tr>
<td>High Modulus Carbon Fiber</td>
<td>300 - 325</td>
</tr>
<tr>
<td>Heavy Copper</td>
<td>385-400</td>
</tr>
</tbody>
</table>
7.3.2 Convection

Convection refers to the thermal transfer of heat from one object (DSP) to the ambient environment typically by means of air movement (fan). Convection or air movement can be pulled or pushed across the DSP depending on the application. If a fan is attached to the DSP the direction is usually to force the air away from the DSP where as if the system or application board includes external cooling fans the air direction can be either direction (push or pull). Air movement in any enclosure involves a plenum whether intended or not, it is always best to optimize the air movement to maximize the effects and minimize any excessive back pressure on the fan (to maximize fan life and noise).

7.4 Mechanical Compression

Mechanical compression, especially where conduction cooling is concerned is important. Excessive compression may improve thermal transfer but also increases the risk of damage to the DSP or inducing added electrical shorts between BGA balls on the application hardware. Excessive mechanical compression is typically noted when using BGA sockets or interfacing a heat sink/enclosure indirect contact with the DSP. Refer to the DSP data sheet and all relevant application notes regarding mechanical compression and BGA assembly. All TI package data sheets provide seating plane specifications defining the maximum compression for the respective BGA package.

7.5 PCB Material Selection

Proper PCB (printed circuit board) material (also referred to as PWB - printed wiring board) has a large impact on the overall system design. Materials range from low cost FR4 to high end ceramic material with other variations in between. Unfortunately what works well for a high performance application where signal integrity and propagation delays are important doesn't work as well as a thermal transfer medium.

The following table illustrates the tradeoff between thermal dissipation and propagation delays for several commonly used materials. Basic calculations were performed using a microstrip topology, Stripline configurations will have faster propagation times.

<table>
<thead>
<tr>
<th>Material</th>
<th>Model</th>
<th>$E_r$</th>
<th>$T_{PD}$ per inch (pS)</th>
<th>Thermal Conductivity W/mK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>N/A</td>
<td>1</td>
<td>90.95</td>
<td>0.024</td>
</tr>
<tr>
<td>PTFE/Glass</td>
<td>2.2</td>
<td></td>
<td>111.31</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>ULTRALAM</td>
<td>2.4 - 2.6</td>
<td>114.36</td>
<td></td>
</tr>
<tr>
<td>3070</td>
<td>RO3730</td>
<td>3.0</td>
<td>123.03</td>
<td>0.45</td>
</tr>
<tr>
<td>3000</td>
<td>RO3003</td>
<td>3.0</td>
<td>123.03</td>
<td>0.50</td>
</tr>
<tr>
<td>IS680</td>
<td>IS680</td>
<td>2.8</td>
<td>120.21</td>
<td>0.32</td>
</tr>
<tr>
<td>7000</td>
<td>SYRON</td>
<td>3.4</td>
<td>128.49</td>
<td>0.35</td>
</tr>
<tr>
<td>IS620</td>
<td>IS620</td>
<td>3.54 - 3.59</td>
<td>130.34</td>
<td>0.35</td>
</tr>
<tr>
<td>4000</td>
<td>RO4000</td>
<td>3.55</td>
<td>130.48</td>
<td>0.64</td>
</tr>
<tr>
<td>GETEK</td>
<td>GETEK</td>
<td>3.5 - 3.8</td>
<td>129.82</td>
<td>0.4</td>
</tr>
<tr>
<td>250HR</td>
<td>FR250</td>
<td>3.90 - 4.0</td>
<td>135.00</td>
<td>0.4 - 0.5</td>
</tr>
<tr>
<td>FR408</td>
<td>FR4</td>
<td>3.75 - 3.81</td>
<td>133.08</td>
<td>0.4</td>
</tr>
<tr>
<td>FR406</td>
<td>FR4</td>
<td>3.92 - 4.0</td>
<td>135.25</td>
<td>0.3 - 0.4</td>
</tr>
</tbody>
</table>
Materials that satisfy both conditions tend to be most costly and not used in mass production of recently evaluated DSP application hardware. Selection of material is paramount to a successful design. Special attention must also be kept when evaluating a material for internal or external traces / planes.

7.6 PCB Copper Weight

Proper copper thickness (referred to as planes) is important to the overall impedance, thermal management, and current carrying capabilities of the design. During the examination and review of all application hardware it is important to consider each of these variables.

As a general rule of thumb, the inner layers or planes of most PCBs are typically 1 oz. copper while the outer layers are 0.5 oz. copper. Outer layers receive solder masking which in the finished product is usually similar to the 1 oz. inner copper weight. The following table provides basic information regarding copper weight, thickness and current carrying capabilities (other factors can positively or negatively affect these specifications).

<table>
<thead>
<tr>
<th>Cu Weight</th>
<th>Cu Thickness (mils)</th>
<th>Cu Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 oz</td>
<td>2.8</td>
<td>0.07112</td>
</tr>
<tr>
<td>1.0 oz</td>
<td>1.4</td>
<td>0.03556</td>
</tr>
<tr>
<td>½ oz</td>
<td>0.7</td>
<td>0.01778</td>
</tr>
</tbody>
</table>

The follow graph (Figure 11) illustrates the relationship between trace width, copper thickness (1 oz. shown) and current carrying capability.
It is important to properly match the weight of the internal layers against the power requirements, thermal needs, and impedance stack up.
8 General Requirements and Considerations

The information contained in this document is only intended to provide a general background to thermal management for the DSP. Ultimately it is the integrator, intermediate application developer, or the end user (collectively referred to as “User”) that must evaluate the system as it pertains to proper thermal management of Texas Instruments DSPs.

Each end application is different, regardless of whether or not the application is designed for the same market space. Design topologies, components, and materials as described briefly in this document account for many of the independent conditions required to properly evaluate the thermal design. It is the “Users” responsibility to correctly apply the variables including environmental conditions to the specific surface nodes of the Delphi compact model. Users can elect to define environmental conditions based on modeling (of the environment) or by establishing boundary conditions in terms of specific heat transfer coefficients. Ultimately the constrains and variables used will be constrained by the tools available and time allotted for the analysis. Certain classes of simulation and modeling tools offer better accuracy and are always recommended.

Texas Instruments recommends to use of Network Compact Models like the Delphi model and intend to supply such a model for all new DSPs.
9 References

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- Lee, Van Au, Morgan, Construction/Spreading Resistance Model for Electronics Packaging, ASME 1995
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- Lee, Optimum Design and Selection of Heat Sinks
- Thermal Characteristics of Linear and Logic Packages Using JEDEC PCB Designs (SZZA017)
- Package Thermal Characterization Methodologies (SZZA003)
- JESD51, Methodology for the Thermal Measurement of Component Packages (Single Semiconductor Device)
- JESD51-2, Integrated Circuits Thermal Test Method Environmental Conditions - Natural Convection (Still Air)
- JESD51-3, Low Effective Thermal Conductivity Test Board for Leaded Surface Mount Packages
- JESD51-5, Extension of Thermal Test Board Standards For Packages With Direct Thermal Attachment Mechanisms
- JESD51-6, Integrated Circuit Thermal Test Method Environmental Conditions - Forced Convection (Moving Air)
- JESD51-7, High Effective Thermal Conductivity Test Board for Leaded Surface Mount Packages
- JESD51-8, Integrated Circuit Thermal Test Method Environmental Conditions - Junction to Board
- JESD51-9, Test Boards for Area Array Surface Mount Package Thermal Measurements
- JESD51-10, Test Boards for Through-Hole Perimeter Leaded Package Thermal Measurements (not used, provided only for reference)
- JESD51-11, Test Boards for Through-Hole Area Array Leaded Package Thermal Measurement (not used, provided only for reference)
- JESD15, Thermal Modeling Overview
- JESD15-1, Compact Thermal Modeling Overview
- JESD15-2, Terms and Definitions for Modeling Standards
- JESD15-3, Two-Resistor Compact Thermal Model Guideline
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