

Application Note

Sitara MCU Thermal Design



ABSTRACT

Temperature, both internal and external to the package, can have a great influence on the characteristics of a device. The temperature of the die within the package can affect both the functionality and reliability of a device. Device packages can also become too hot and present a safety concern to users. All of these reasons and more are why the thermal properties of a printed circuit board should be heavily reviewed. Whether it is copper thickness or layer count, there are many different aspects of the PCB design that affect the thermal characteristics of the board. This document will describe many best practices and rules of thumb when it comes to thermal dissipation in PCB design. The in-depth discussion will then be put to the test through a real-world experiment that measures the junction temperature of two different AM263x evaluation modules (EVMs). The results of the experiment will be reviewed and justify how the different thermal design choices that were made in both EVMs affected the thermal performance.



Note

While this document contains specific information and testing on the AM263x device and the AM263x evaluation modules, the thermal design principles that are described throughout the application note are applicable to all Sitara™ microcontrollers.

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1 Introduction

Note

This document serves to explain some best practices for thermal dissipation when designing a board. For the most accurate thermal representation of a system, import the device thermal model as well as the board properties into a thermal simulation program. For more information on using the Thermal Model, see the [Section 6](#).

1.1 How to Use This Application Note

Many factors can influence the junction temperature of a device. Therefore, it is important to understand what PCB design choices impact thermal resistance and subsequently junction temperature.

- [Chapter 3: Thermal Resistance Overview](#)
 - The thermal resistance overview explains all of the thermal resistances to consider in a system and how the thermal resistance between junction and ambient temperature is heavily influenced by PCB design.
- [Chapter 4: Board Design Choices that Affect Thermal Performance](#)
 - There are many factors to consider when designing a PCB. This chapter details how certain factors affect the ability for heat to dissipate away from the device and lower junction temperature. The design choices for two different AM263x EVMs are detailed for each of the factors and best practices are included in each section.
- [Chapter 5: Thermal Design Best Practices Review](#)
 - This chapter combines all of the best practices for each design factor into a single page for quick and easy review.
- [Chapter 6: AM263x EVM Thermal Comparison with Data](#)
 - A testing script was developed to measure the junction temperature across an ambient temperature sweep with two different AM263x EVMs. The results detail how the PCB design differences between the two EVMs impacted the thermal resistance between junction and ambient temperature. Operating power and thermal resistance were also recorded across the ambient temperature sweep.
- SoC Power Estimation Tool
 - Each Sitara MCU has an associated Power Estimation Tool (PET) under the **Design tools & simulation** section of the device product page. The PET is used to approximate the power consumption for the device under the operating conditions of the designed system.
- [Chapter 7: Using the Thermal Model](#)
 - When a PCB design is complete, then the best practice is to import the design and any enclosure into a thermal simulation software. The PET output provides an estimation of the power consumption that can be used to produce a more realistic thermal model of the system. The simulations can calculate junction temperature for a given system and environment parameters by using the SoC thermal model. The device thermal model can be found under the **Design tools & simulation** section of the device product page.

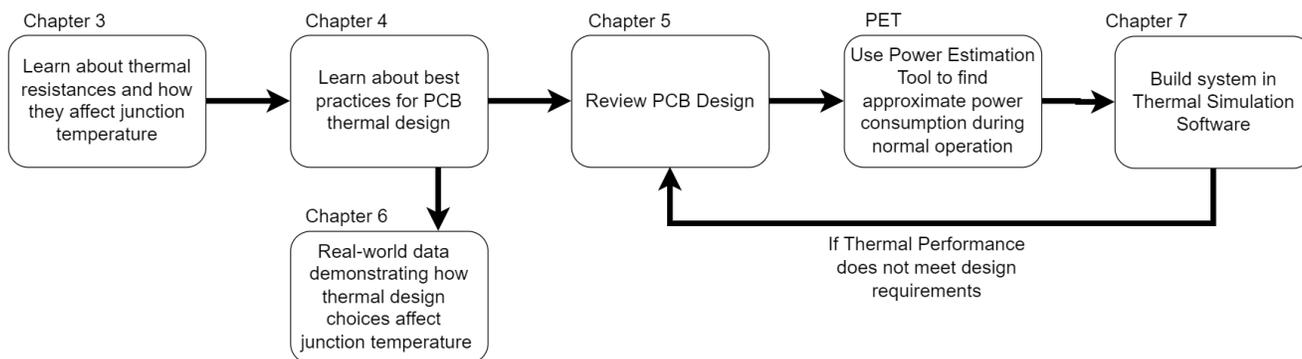


Figure 1-1. Application Note Chapter Flow

1.2 Glossary

Table 1-1. Glossary and Acronym Definitions

Term	Definition
Junction Temperature	The temperature within a package near a hotspot on the die
Ambient Temperature	The temperature of the surrounding free air of a system
Lid (Case) Temperature	The temperature of the surrounding material of a package
$R\theta_{JA}$	Thermal resistance between junction and ambient temperature
$R\theta_{JC}$	Thermal resistance between junction and case (lid) temperature
$R\theta_{CA}$	Thermal resistance between case (lid) and ambient temperature
$R\theta_{JB}$	Thermal resistance between junction and board temperature
$R\theta_{BA}$	Thermal resistance between board and ambient temperature
$R\theta_{Via}$	Thermal resistance of a thermal via array
$R\theta_{Cu}$	Lateral Thermal resistance of a planar copper pour
$R\theta_{FR-4}$	Thermal resistance between junction and ambient temperature
$R\theta_{SA}$	Thermal resistance between the surface area of a PCB and the ambient temperature
Thermocouple	A junction between two conductors that produces a voltage depending on the material that can be mapped to specific temperature values
AEC-Q100	As defined by the Automotive Electronics Council, AEC-Q100 is a qualification given to a device that can sustain stress tests with guaranteed level of quality and reliability for a given temperature range.
Acronyms Used in This Document	
SoC	System on a chip
JEDEC	Joint Electron Device Engineering Council
LP	LaunchPad Development Kit
CC	Control Card Development Kit
RTI	Real time interrupt module that provides a timer functionality

2 Thermal Resistance Overview

2.1 Junction Vs. Ambient Temperature

Before learning about the intricacies of thermal design, it is important to develop an understanding of the different temperatures of interest on a board. While the temperature on the package lid is what stands out on a thermal camera, the temperature beneath the lid is what determines the functionality of the device. Specifically, the area near hotspots on the die or **junction temperature (T_J)**. Junction temperature is influenced by many things but there is a clear relationship between the junction temperature and the temperature of the free air surrounding a system or **ambient temperature (T_A)**. This relationship between junction temperature and ambient temperature can be defined by the thermal characteristic: R θ_{JA} or the thermal resistance between junction and ambient temperature.

$$\frac{T_{\text{Junction}} - T_{\text{Ambient}}}{\text{Operating Power (Watts)}} = R\theta_{JA} \left(^\circ\text{C/W} \right) \quad (1)$$

Thermal properties can be represented similarly to a simple electrical circuit. From this perspective, "Ohm's law" still applies to the thermal "circuit". The operating power of the device in Watts is analogous to the current of the circuit and the thermal resistance between the two temperatures is the resistance.

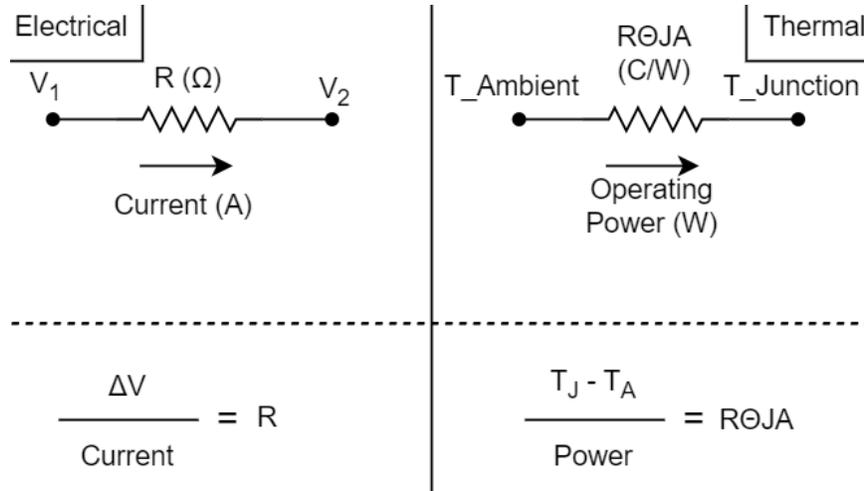


Figure 2-1. Electrical vs Thermal Nodal Analysis

Note

R θ_{JA} is not a constant value and depends heavily on the PCB design.

The [AM263x Sitara™ Microcontrollers Data Sheet](#) lists values for thermal resistance characteristics but these values do not always tell the whole story. The thermal resistance characteristics in the data sheet are based upon a specific test condition based on a Joint Electron Device Engineering Council (JEDEC) defined 2S2P system.

Note

Due to the thermal resistance values in the data sheet being based on the [JEDEC defined, 2-signal and 2-power layer \(2S2P\) system](#), it is important to not use these values to calculate junction temperature with a known ambient or lid temperature. The AM263x has a thermal manager module with two thermal sensing ADC's near hotspots of the die to record junction temperature.

2.2 Package Defined Thermal Resistance Characteristics

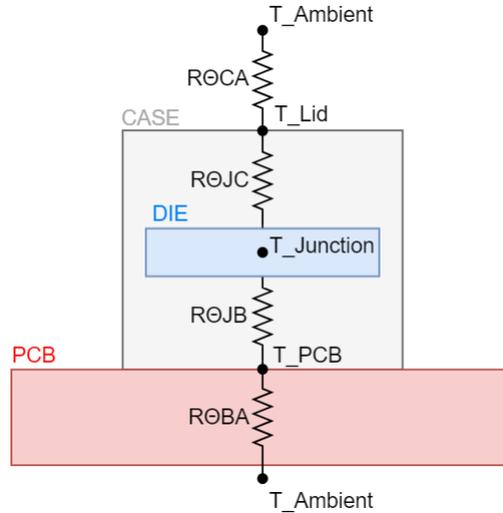


Figure 2-2. Thermal Resistances of a System

$R_{\Theta_{JA}}$ is dependent on many factors and some of these thermal resistance characteristics are constant across system designs. Figure 2-2 shows the various thermal resistances in a system. The constant characteristics are defined by the ability for heat to dissipate from the die to the external parts of the package case. The thermal resistance between the junction and the board is defined by $R_{\Theta_{JB}}$ and the thermal resistance between the junction and case (lid) is defined by $R_{\Theta_{JC}}$. The lid of the package also has a thermal resistance between the lid and the ambient temperature or $R_{\Theta_{CA}}$. Since the AM263x only has one package type, $R_{\Theta_{JC}}$ and $R_{\Theta_{JB}}$ are constant. $R_{\Theta_{CA}}$ can be lowered by applying air flow over the lid.

Figure 2-3 shows the circuit representation of high-level thermal resistances, whether or not they vary between designs.

Note

In order to lower the junction temperature of the System on a chip (SoC), system design choices must be made to help with the thermal dissipation of the PCB or air flow must be introduced to help with the board/case to ambient thermal resistance. For more information on the board defined thermal resistances, refer to [Section 2.3](#).

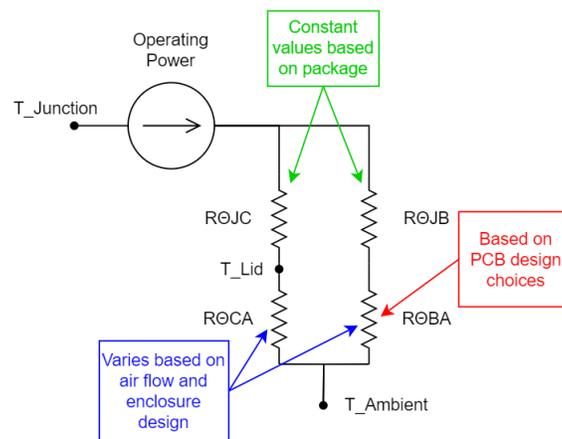


Figure 2-3. Basic Thermal Resistances of a system

2.3 Board Defined Thermal Resistances

The design of a PCB will have a strong correlation to the difference between junction and ambient temperature. The ideal goal is for the junction temperature to be as close as possible to the ambient temperature but when the heat is not able to efficiently diffuse away from the SoC, then the delta between junction and ambient temperature will be larger. The thermal resistance between the board and ambient temperature can be broken up into four separate thermal resistances that will have varying values based on the system design:

- Thermal resistance of a thermal via ($R\Theta_{Via}$)
- Thermal resistance of a copper plane ($R\Theta_{Cu}$)
- Thermal resistance of FR-4 Laminate ($R\Theta_{FR-4}$)
- Thermal resistance of board surface area and ambient temperature ($R\Theta_{SA}$)

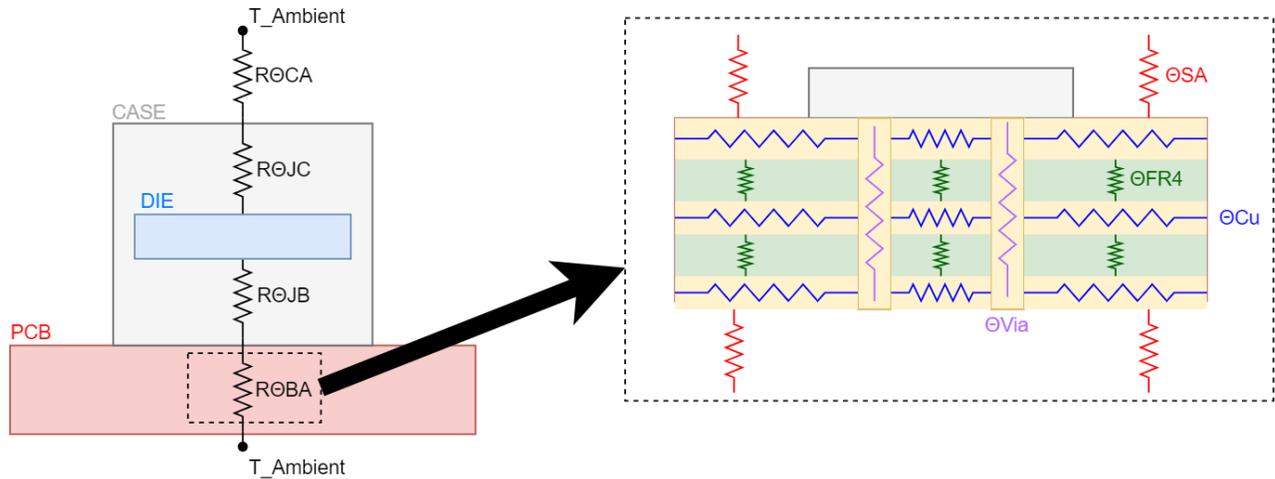


Figure 2-4. Breakdown of $R\Theta_{BA}$

It is easy to imagine how some simple design choices can help with decreasing the $R\Theta_{BA}$ which subsequently decreases the $R\Theta_{JA}$. A few examples of design choices to help with thermal performance are increasing copper volume of thermal vias, adding additional copper layers, or increasing board size. For a fullbreak down of design choices that affect thermal performance, refer to [Section 3](#).

3 Board Design Choices that Affect Thermal Performance

The thermal design of a PCB can impact various aspects of a design:

Table 3-1. Thermal Design Factors

Factor	Description
Functionality/Reliability	Will the system work in the expected temperature range?
Cost	Will changes for thermal considerations make the board cost too much?
Weight	Is there a weight restriction that would limit thermal dissipation options?
User experience	Will the user burn themselves if they touch the board during operation?

All of the aforementioned factors must be considered when designing a PCB. There are many effective solutions to limit the $R\Theta_{JA}$ of a system. The design choices that should be considered when reviewing the thermal design of the board are the following:

- [Position, dimensions, and number of thermal vias](#)
- [Board size](#)
- [Air flow, heat sinking, and enclosures](#)
- [Ground layer copper pour thickness](#)
- [Relative position of heat emitters](#)
- [Number of layers](#)
- [Limiting breaks in thermal pathing](#)

3.1 Thermal Vias

The thermal via array implementation is arguably the most important aspect of thermal design for the AM263x since unless there is a heatsink used for the BGA package, the thermal vias are the only heat-sinking thermal connection for the BGA package. The thermal vias for the AM263x are in the form of the ground return vias attached to each VSS pin of the BGA.

The thermal resistance of thermal vias ($R\Theta_{vias}$) relates to the total thermal resistance of all thermal vias beneath the SoC. Each individual thermal via is analogous to a resistor where the equivalent resistance of all resistors is similar to many parallel resistors. Similar to an increasing number of parallel resistors and equivalent resistance, there are diminishing returns on the equivalent thermal resistance with each additional thermal via. For example, in a case where a single via has a thermal resistance of 50°C/Watt then [Figure 3-1](#) shows the relationship between number of thermal vias and the equivalent thermal resistance (assuming that all vias have the exact same properties).

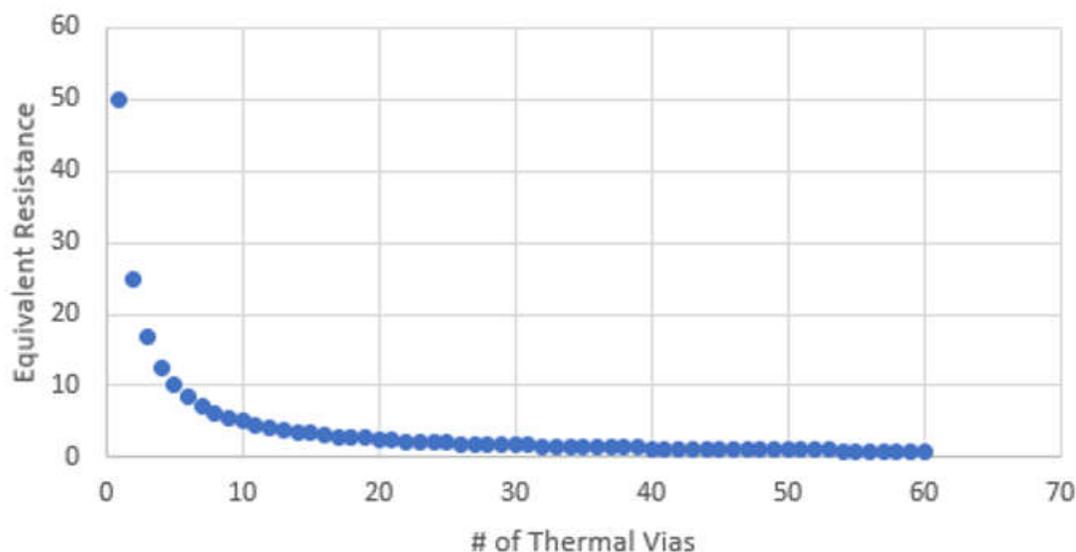


Figure 3-1. Equivalent Resistance Graph for Thermal Vias

The dimensions of a thermal via are what determine a single thermal via's thermal resistance. a general rule of thumb is that $R\theta_{vias}$ is estimated by the following equation:

$$\frac{1}{\lambda(Cu) \frac{Length}{Area}} = R\theta_{Single Via}$$

Where $\lambda(Cu)$ is the conductivity of copper or 4 Watts per meter-kelvin, length refers to the length of the via, and the equation for thermal via area is:

$$\pi * [(Drill Hole Radius)^2 - (Drill Hole Radius - plating thickness)^2]$$

Figure 3-2 shows an example of the thermal via array with 8mil holes and 10 mil trace width from the BGA to the thermal vias.

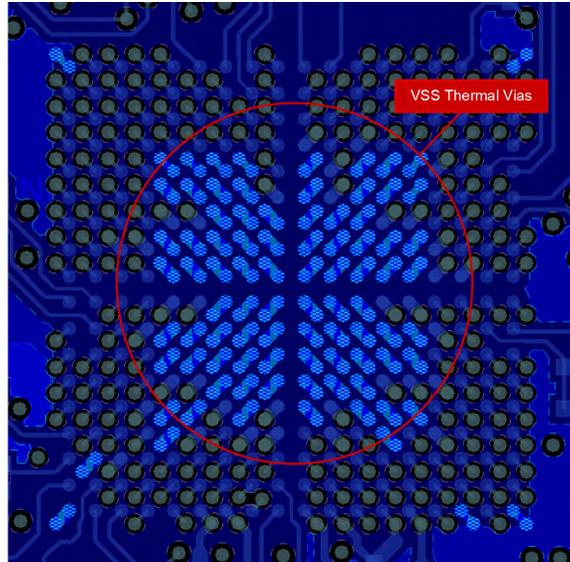


Figure 3-2. AM263x controlCARD Thermal Vias

For best thermal performance:

- Use vias on each VSS pin of the BGA
- Use widest possible traces from the BGA to the via
- Use the largest possible drill diameter
- Conductively fill the thermal vias

Table 3-2. AM263x EVM Thermal Vias Comparison

Measurement	TMDSCNCD263	LP-AM263
Number of thermal vias	90	90
Drill hole diameter	8 mil	8 mil
Plating Thickness	35 um	20-30 um
Conductively filled vias	Resin filled	Empty cavity

3.2 Board Size

Board size is important because a larger board also results in larger copper pour for ground layers to disperse heat while also providing more surface area to diffuse the heat from the surface of the board to the surrounding air. Total board size being larger does not guarantee better thermal performance because it is important to consider other thermal characteristics of the board as well. A board can have a large surface area but also [breaks or bottlenecks in the thermal pathing](#) that result in negligible returns on the thermal resistance of the surface area of the board. Additionally, even if a board is large, if [all major heat dissipators are all in the same area](#) then the result will be a worse thermal performance.

For best thermal performance:

- Make the board as large as possible
- Place the SoC away from the edge of the board

Table 3-3. AM263x EVM Board Size Comparison

Measurement	TMDSCNCD263	LP-AM263
Board dimensions	105.76 x 82.81 mm + 6.09 mm length of HSEC	195.58 x 58.42 mm
Approx. Surface area	9,300 mm ²	11,400 mm ²
Distance from SoC to board edge	13.39 mm	22.89 mm

3.3 Air Flow, Heat Sinking, and Enclosures

There are a few external influences that affect the thermal resistance between the junction and ambient temperature. If the system is going to be designed within an enclosure, a new additional thermal resistance must be accounted for. Now, what was previously the thermal resistance between junction and ambient air, is only the thermal resistance between the junction temperature and the air within the enclosure. Any changes in ambient temperature will have a greater impact on the junction temperature. It is important to offset the additional thermal resistance that an enclosure provides by improving the thermal resistance of other areas of the system.

One way to improve the thermal performance of a system within an enclosure is to introduce air flow. By including a fan on a cutout of the enclosure, the thermal resistance that is created by the enclosure is minimized. Additionally, air flow in general will decrease the thermal resistance of external surface area such as the package lid or the PCB itself.

Attaching a heat sink is a general solution to address thermal issues. However, it should be noted that using a heat sink only decreases the thermal resistance between junction and case temperature. A PCB with significant thermal dissipation flaws will not be fixed simply by adding a heat sink.

For best thermal performance:

- Use an enclosure that is optimized for thermal performance
- Include fans in the enclosure design
- Use a heat sink attached to the BGA Case lid
- Maintain consistent air flow to the system

Table 3-4. AM263x EVM External Cooling Comparison

Measurement	TMDSCNCD263	LP-AM263
Air Flow	N/A	N/A
Heat Sink	N/A	N/A
Enclosure	N/A	N/A

3.4 Copper Thickness

The copper thickness is important for thermal performance as the ground copper pours are responsible for dispersing the heat that is traveling from the thermal vias. Copper thickness is tied to the copper weight per square foot. Typically, PCBs will have either 0.5 oz/sq ft or 1.0 oz/sq ft.

$$\frac{1}{\lambda(\text{Cu})} \left(\frac{\text{Length}}{\text{Width} * \text{Thickness}} \right) = R\theta \left(\text{Copper layer} \right)$$

Where $\lambda(\text{Cu})$ is the conductivity of copper or 4 Watts per meter-kelvin, length and width refers to the length and width of the copper plane.

For best thermal performance:

- Maximize the area of each copper layer
- Use heavier copper layers

Table 3-5. AM263x EVM Copper Thickness Comparison

Measurement	TMDSCNCD263	LP-AM263
Ground layer copper thickness	1.26 mil	1.26 mil
Copper weight	1 oz/sq ft	1 oz/sq ft

3.5 Relative Position of Heat Emitters

The AM263x device is not the only package that is dissipating heat on a PCB. It is important to make a conscious effort to separate all heat-releasing components or else the thermal resistance between the board and ambient temperature will suffer as a result. Examples of components that run warmer include but are not limited to:

- Other processors or microcontrollers
- Power Management Integrated Chips (PMIC)
- Voltage regulators
- LIN and Ethernet PHY

For best thermal performance:

- Ensure that there is sufficient distance between known heat emitters on the PCB.

Figure 3-3 shows how the LaunchPad was designed to separate low-dropout (LDO) voltage regulator's heat radiation from the AM263x device. The AM263x Control Card is designed with a heat-emitting package near the SoC but the package is responsible for supplying the 25 MHz clock to the SoC. In this instance, the signal integrity of the operating clock is more important than impacting thermal resistance. Because the control card follows other thermal design rules listed in this document, it is easy to overlook the potential impact of one heat-emitting package near the SoC. Figure 3-4 shows the thermal camera view of the AM263x Control Card.

Note

The following images are taken with a thermal camera where the AM263x device was running a max power use-case and the boards soaked at an ambient temperature of 25°C for 15 minutes.

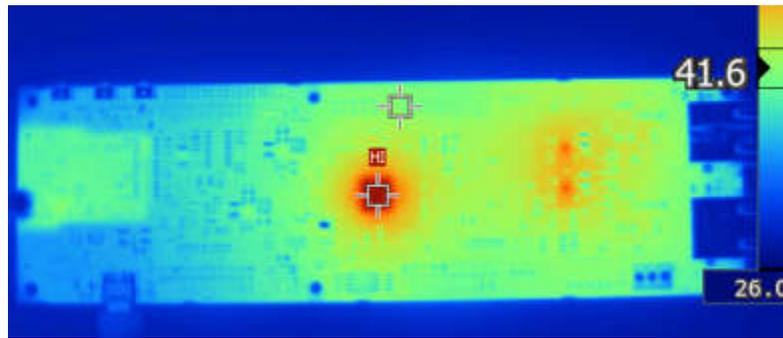


Figure 3-3. LP-AM263x Thermal Camera

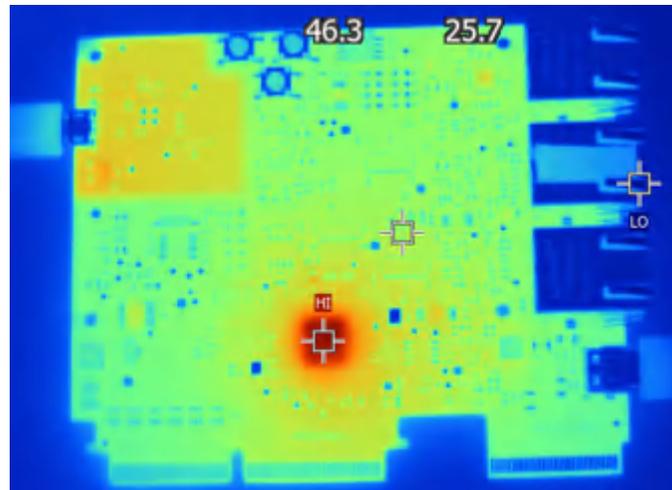


Figure 3-4. TMS263CNCD Thermal Camera

3.6 Layer Count

Similar to increasing copper thickness, increasing the number of ground layer copper pours to distribute heat will significantly improve thermal performance. Increasing the total layer count will also generally decrease thermal resistance but the results will not be as notable if ground layers are not included.

If the system is being designed with less than 6 layers (2 ground layers) then it is critical to ensure all other thermal concerns of the PCB are being minimized through other design choices.

For best thermal performance:

- Increase the total number of layers
- Increase the number of ground layer copper pours

Table 3-6. AM263x EVM Layer Count Comparison

Measurement	TMDS263CNCD	LP-AM263
Total number of layers	10	6
Ground layers	4	2

3.7 Breaks in Thermal Pathing

Similar to how narrowing a water pipe will bottleneck the flow of water, traces and via cutouts can lead to bottlenecks of the thermal dissipation. Each ground layer on the board should be reviewed to make sure that there are no breaks in the thermal pathing. Multiple vias together in a line or array can create a cutout on the ground layer that will negatively impact the thermal flow away from the SoC.

For best thermal performance:

- Review each ground layer and ensure there are no copper pour cutouts that would impede the flow of heat.

4 Thermal Design Best Practices Review

The following list can be reviewed to review whether a board design is following the basic rules for optimizing the thermal dissipation of the SoC. This list captures the rules of thumb that are in each board design choice subsection from [Section 3](#)

Note

For worst-case thermal scenarios, all system design details need to be taken into account, including enclosure characteristics and presence of air flow.

For best thermal performance:

- **Thermal Vias**
 - Use vias on each VSS pin of the BGA.
 - Use the widest possible traces from the BGA to the via in a dogbone fanout.
 - Use the largest possible drill diameter.
 - Use conductively filled thermal vias.
- **Board Size**
 - Make the board as large as possible.
 - Place the SoC away from the edge of the board.
- **Air Flow and Heat Sinking**
 - Use an enclosure that is optimized for thermal performance.
 - Include fans in the enclosure design.
 - Use a heat sink attached to the BGA Case lid.
 - Maintain consistent air flow to the system.
- **Copper Thickness**
 - Maximize the area of each copper layer.
 - Use heavier copper layers.
- **Relative Position of Heat Emitters**
 - Ensure that there is sufficient distance between known heat emitters on the PCB.
- **Layer Count**
 - Increase the total number of layers.
 - Increase the number of ground layer copper pours.
- **Breaks in Thermal Pathing**
 - Review each ground layer and ensure there are no copper pour cutouts that impede heat flow.

5 AM263x EVM Thermal Comparison with Data

5.1 Test Setup and Materials

The materials used for this thermal measurement procedure are as follows:

- MPI Thermal ThermalAir TA-5000A Precise Temperature Forcing System
 - Constant flow of air to control the ambient temperature within the enclosure
- Two National Instruments USB-TC01 Temperature Input Devices
 - Used to record data for the ambient temperature and AM263x lid temperature over time
- Two Type-T thermocouple probes
 - Type-T thermocouple temperature probes have an accurate temperature range of -185°C to 300°C
- Sealed acrylic thermal chamber
 - Allows for ambient temperature to be manipulated by the ThermalAir system
- AM263x Control Card Evaluation Module
- AM263x LaunchPad Evaluation Module

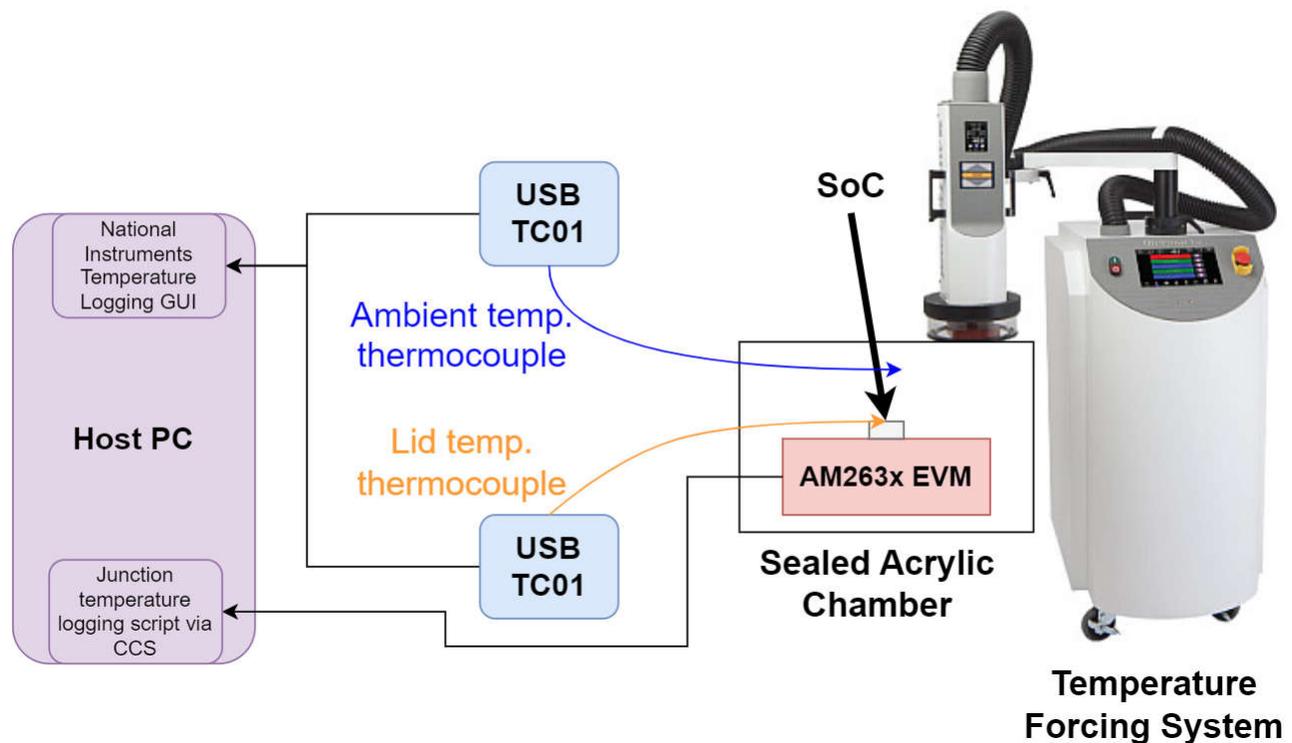


Figure 5-1. Testing Setup Diagram

To conduct the thermal measurements, the Evaluation module is placed within the acrylic thermal enclosure such that it is under the air vent of the ThermalAir system. One of the thermocouple probes is placed onto the middle of the AM263x device package lid and secured using Kapton tape. The other probe is secured to the EVM with Kapton tape above the board to record the ambient temperature of the system. Both thermocouple probes are connected to a NI USB-TC01 device to record the thermal measurements. The USB-TC01 devices are programmed to log the temperature of the connected probe every ten seconds.

The ThermalAir system allows for control of the air flow rate and temperature. For these measurements, the flow rate of air is set to 12.0 standard cubic feet per minute (SCFM). There is a script that is used to configure the temperature of the air stream from the ThermalAir nozzle output. The script increments the temperature of the air flow by 5°C every 10 minutes where the temperature starts at -50°C and ends at 165°C. It should be noted that the ambient temperature within the enclosure will not be the same as the air flow temperature. Before the script begins, the ThermalAir is set to output -50°C air until the enclosure reaches a steady ambient temperature at approximately -30°C.

The Evaluation Modules make use of two different programs that will be run on the R5 cores. The first program is loaded onto R5F_0 and it is responsible for logging the internal junction temperature every ten seconds. The second program is loaded onto cores to simulate a full load on that particular core. The measurements taken in this procedure include when just the logging script is running on R5F_0, when the logging script is running on R5F_0 and R5F_1 is at full load, and when the logging script is running on R5F_0 and R5_1/2/3 are all at full load. The AM263x Control Card is designed with the INA228 power monitor that allows the operating power to be recorded every ten seconds in addition to the junction temperature recordings so that the power consumption can be observed over different values of junction temperature and ambient temperature. The AM263x LaunchPad does not have the INA228 power monitor and these values were not recorded for this EVM.

As with any test environment, there are variables that must be considered. The EVMs and temperature probes were not moved during the course of the three tests on each EVM but there were differences in the test setup for the LaunchPad and Control Card. The position of the temperature probes and EVM itself were approximately in the same position in relation to the air stream nozzle but not in the same exact position. Additionally, since these tests were taken over the course of many days, the temperature of the lab was not constant and has a small impact on the ambient temperature readings within the enclosure.

5.2 Measurement Logging Software

The following section serves to describe the measurement logging script that was run on the EVMs during the ambient temperature sweeps. Before the logging begins, the TSENSE internal junction temperature probes are configured.

In order to enable the temperature controller, the following bits need to be reset TSPSOFF, BGROFF, AIPOFF, and SNSR_MX_HIZ within the TOP_CTRL_TSENSE_CFG register. There are two internal temperature sensors (TSENSE0 and TSENSE1), each of which is located near the hotspots of the device. The SENSOR_SEL register controls the enabling of the individual sensors. For each selected sensor, the FSM requires anywhere between 51 to 54 clock cycles to start the sequences. Once the TSENSE_CFG_ENABLE bit is set, then the temperature measurement is initiated automatically. For more information on the thermal manager, see the *Thermal Manager* chapter within the [AM263x Sitara™ Microcontrollers Technical Reference Manual](#).

The program makes use of the RTI timer module to start a 10 second timer between measurement readouts. For more information about the RTI timer module, see the *Timer Modules* chapter within the [AM263x Sitara™ Microcontrollers Technical Reference Manual](#).

The AM263x Control Card features two INA228 power monitors for the 3.3 V and 1.2 V rail current measurements. The AM263x communicates with the INA228 power monitors through I2C commands. For further information on configuring the INA228 devices on the AM263x Control Card, see [Monitoring Bus Voltage and Power Measurement on AM263x MCU Using INA226/INA228](#).

Section 5.2 shows the overview of the measurement recording program in a high-level flow diagram.

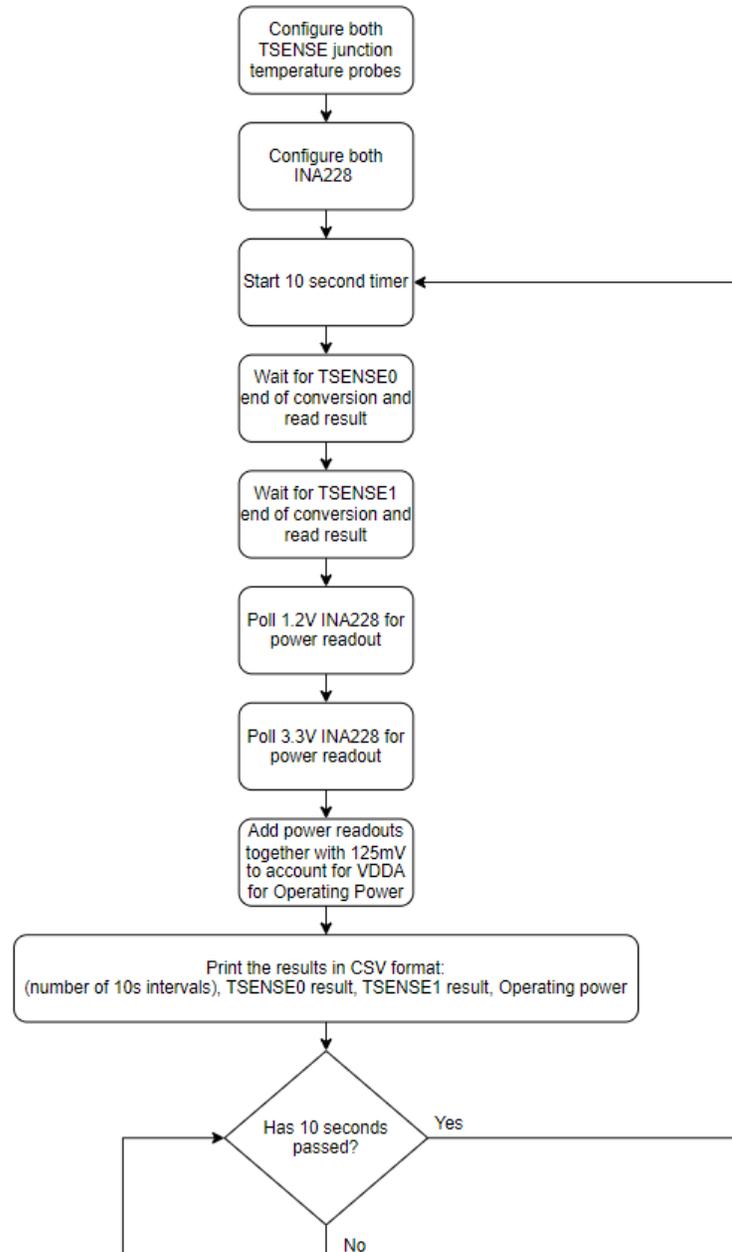


Figure 5-2. Logging Software High-Level Flow Diagram

5.3 AM263x EVM Comparison

The two EVMs that were used to observe junction temperature in relation to ambient temperature are the AM263x Control Card and AM263x LaunchPad. These two systems have different qualities and design choices that affect the thermal performance of the AM263x SoC. Table 5-1 details the relevant differences in PCB design.

Table 5-1. AM263x EVM Comparison

Measurement	TMDSCNCD263	LP-AM263
Number of thermal vias	90	90
Drill hole diameter	8 mil	8 mil
Plating thickness	35 um	20-30 um
Conductively filled vias	Resin filled	Empty cavity

Table 5-1. AM263x EVM Comparison (continued)

Measurement	TMDSCNCD263	LP-AM263
Board dimensions	105.76 x 82.81 mm + 6.09 mm length of HSEC	195.58 x 58.42 mm
Approx. Surface Area	9,300 mm ²	11,400 mm ²
Distance from SoC to board edge	13.39 mm	22.89 mm
Ground layer copper thickness	1.26 mil	1.26 mil
Copper weight	1 oz/sq ft	1 oz/sq ft
Total number of layers	10	6
Number of ground layers	4	2

Based on the comparison table, it can be theorized that the thermal performance of the AM263x Control Card will be better than the AM263x LaunchPad. Despite the Launchpad having a slightly larger surface area, the Control Card features four ground layers for improved heat dispersion. Designing the PCB with twice as many ground layers should have a very apparent impact on the relationship between junction temperature and ambient temperature.

5.4 Measurement Results

Note

For a concise list of best thermal design best practices, see [Section 4](#). The results of the testing exemplify how the thermal design choices of two different EVMs with the same SoC influence the thermal performance.

The following subsections detail the results of the various measurements and calculations for the thermal testing procedure. For these sections, graphs will reference the EVMs as CC for AM263x Control Card and LP for AM263x LaunchPad. The graphs will also refer to the test configuration when only the logging script is running on R5_0 as <EVM>_noLoad. When the other cores are running at full load then the graph will refer to those lines as either <EVM>_Load1 to for full load on the first R5FSS cluster or <EVM>_Load123 for full load on both R5FSS clusters.

5.4.1 Lid Temperature Readings

The lid temperature readings remained relatively consistent with little variance across ambient temperature regardless of R5 core utilization. It would be expected that the LP and CC SoC lid readings would be practically the same due to the package-defined $R\theta_{JC}$ value. Differences between the graphs can be attributed to the different amounts of tape on the package as well as the position of the thermocouple probe, both of which affect the thermal resistance between the case and ambient air temperature or $R\theta_{CA}$.

Note

The ThermalAir system was programmed to soak at each temperature for 10 minutes before incrementing up by 5°C. The thermalAir airstream output began at -50°C and increments up to 165°C. This results in an ambient temperature range of approximately -30°C to 118°C.

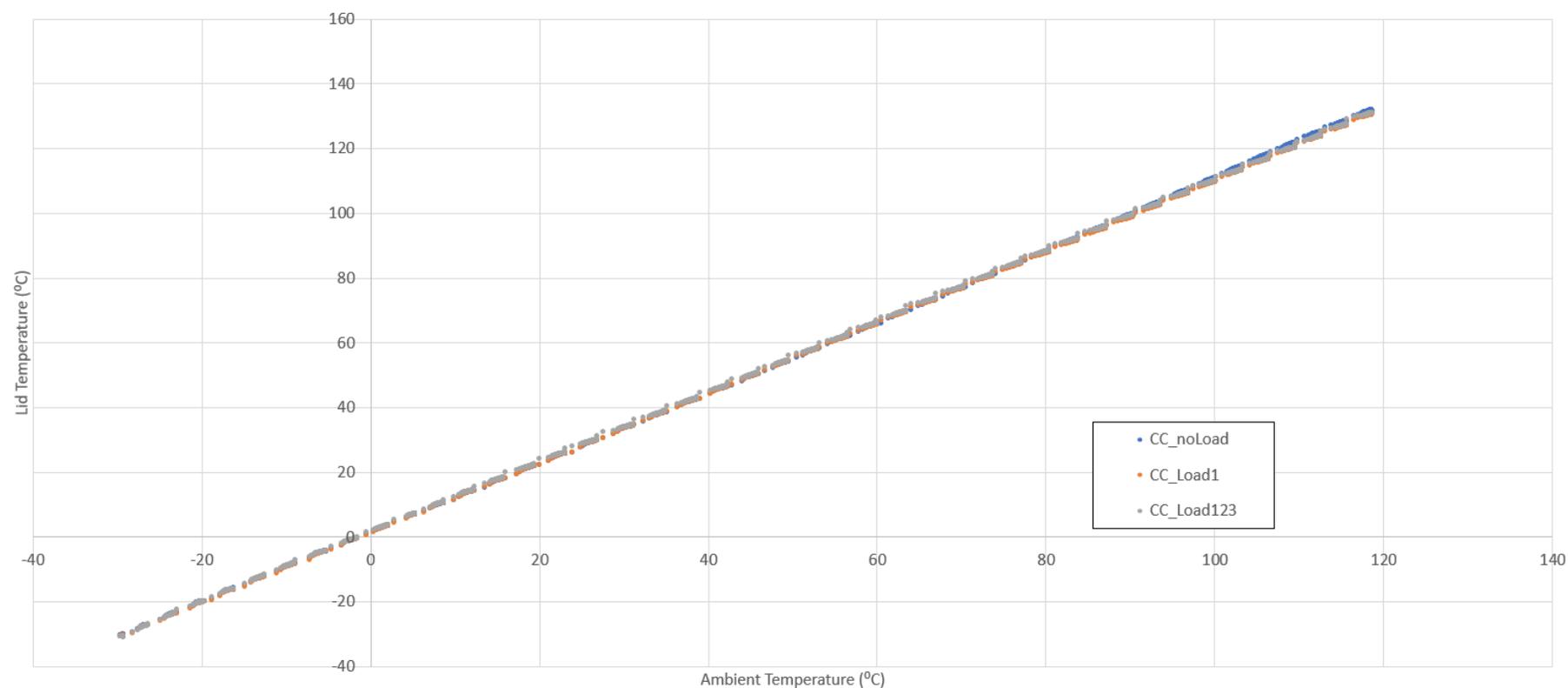


Figure 5-3. AM263x Control Card Lid Temperature Reading

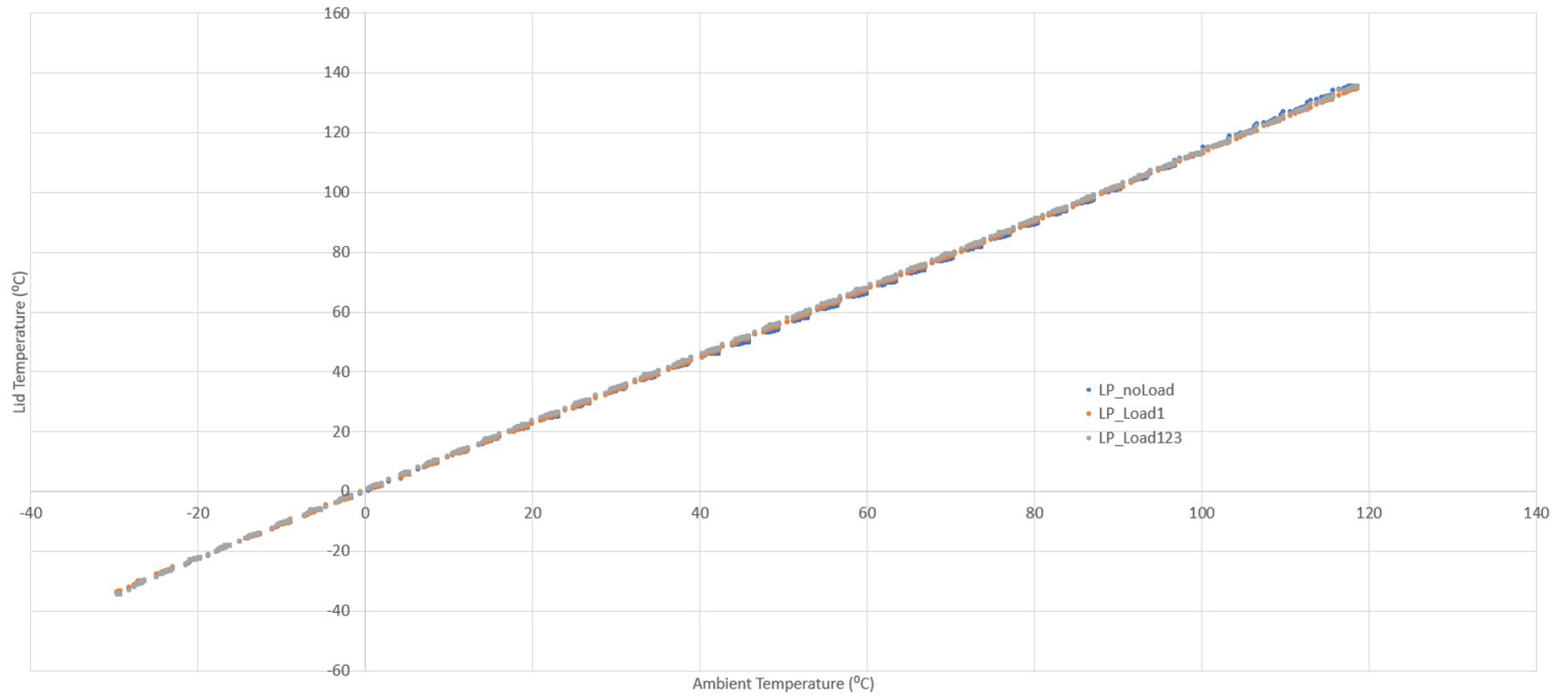


Figure 5-4. AM263x LaunchPad Lid Temperature Reading

5.4.2 Power Readings over Temperature

The Operating Power was recorded during the measurements by polling the two INA228 power monitors for the 1.2 V and 3.3 V supply rail operating power. These two values were added together and then 125 mV was added to account for the VDDA supply rail operating power.

The operating power was recorded in four different configurations. The first three included Kapton tape on the package for lid temperature measurements. These three configurations included when only the logging script was run on R5_0 (CC_noLoad), the logging script run on R5_0 and R5_1 run at full load (CC_Load1), and the logging script run on R5_0 and R5_1/2/3 run at full load (CC_Load123). The final configuration for power measurement was when no Kapton tape was on top of the package, resulting in a noticeably decreased operating power due to the decreased thermal resistance between case temperature and ambient temperature or $R\theta_{CA}$.

Table 5-2. Power Measurements at Temperature Extremes for the AM263x Control Card

ThermalAir Airstream Output	Ambient Temperature Reading	CC_noLoadNoTape Power	CC_noLoad Power	CC_Load1 Power	CC_Load123 Power
-50°C	-29.4 °C	1.21 W	1.30 W	1.32 W	1.36 W
165°C	118.6 °C	1.60 W	1.71 W	1.73 W	1.77 W

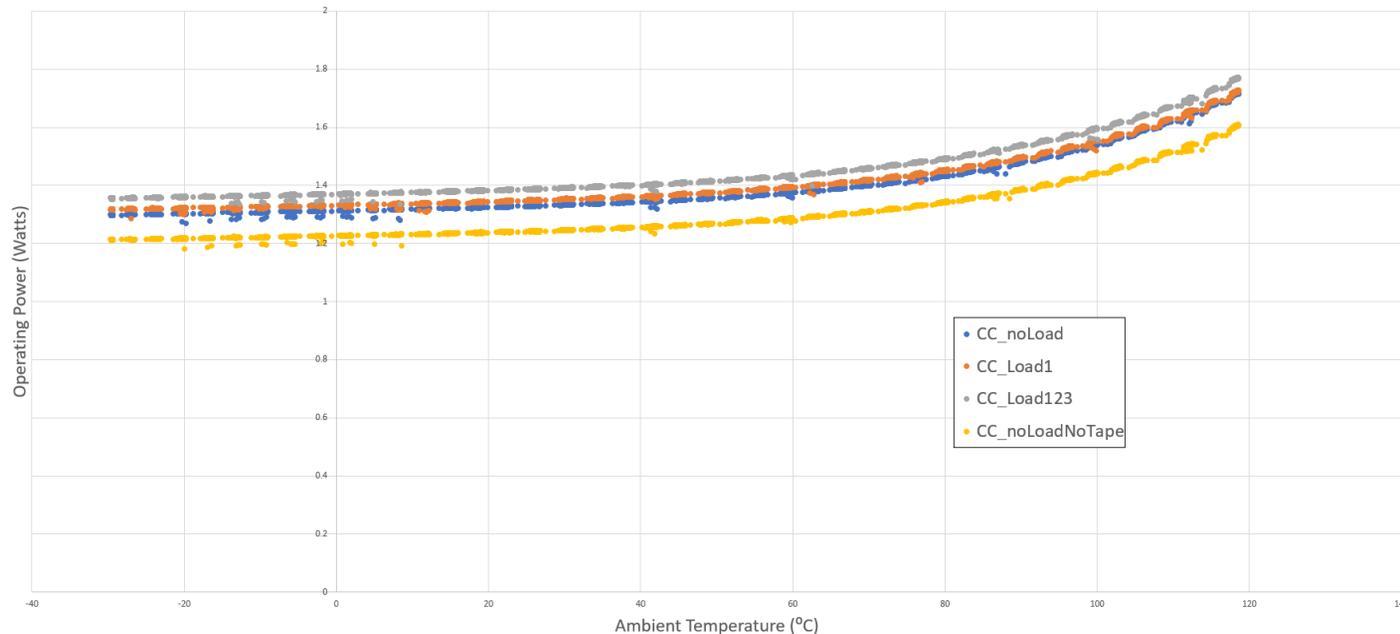


Figure 5-5. AM263x Control Card Device Operating Power Across Ambient Temperature Sweep

5.4.3 Calculated Thermal Resistance Values

Since the Control Card allows for the operating power to be recorded during the ambient temperature sweep, the thermal resistance between junction temperature and ambient temperature or $R\theta_{JA}$ can be calculated using the following equation:

$$\frac{T_{\text{Junction}} - T_{\text{Ambient}}}{\text{Operating Power (Watts)}} = R\theta_{JA} \left(^\circ\text{C/W} \right) \quad (2)$$

Table 5-3 shows the values for the max and average calculated values of $R\theta_{JA}$. The [AM263x Sitara™ Microcontrollers Data Sheet](#) includes a table that describes the *Package Thermal Characteristics*. An excerpt of the *Package Thermal Characteristics* table is shown in Table 5-4. Within this table, the values for thermal resistance based on a JEDEC defined 2S2P system can be found where the system is in the worst case device power consumption. The worst case values for $R\theta_{JA}$ are 12.9, 11.8 and 11.1 °C/W for 1, 2, and 3 meters per second air flow, respectively. For the non-simulated real world experiment, the calculated **max** values for $R\theta_{JA}$ based upon measurements taken during the ambient temperature sweep are in line with the worst case device power consumption values from the data sheet. While the max values of $R\theta_{JA}$ are near the worst case spec from the data sheet, the average value for $R\theta_{JA}$ is considerably lower.

Note

Each measurement configuration was only run once and variance for each module measurement can result in calculated values of $R\theta_{JA}$ having variance as well.

Table 5-3. Thermal Resistance Calculations

Measurement	$R\theta_{JA}$ Max (°C/W)	$R\theta_{JA}$ Average (°C/W)
CC only logging script with no Kapton tape on SoC	11.32	7.33
CC only logging script	11.88	8.16
CC logging script + Load Core 1	11.14	7.91
CC logging script + Load Cores 1,2,3	11.19	7.95

Table 5-4. AM263x Data Sheet Package Thermal Characteristics

Parameter	Thermal Resistance Description	°C/W	AIR FLOW (m/s)
$R\theta_{JC}$	Junction to case	5.6	N/A
$R\theta_{JB}$	Junction to board	5.7	N/A
$R\theta_{JA}$	Junction to free air	18.6	0
$R\theta_{JA}$	Junction to moving air	12.9	1
		11.8	2
		11.1	3

5.4.4 Recorded Junction and Ambient Temperatures

The temperature sweep program soaked at each ThermalAir output temperature for ten minutes during the temperature sweep. The soaking time allowed the ambient and junction temperatures to plateau. Since there are 44 steps of ten minute soaks in the incrementation from -50 to 165 °C, then there are around 26,400 seconds per measurement sweep or around 2,640 ten second intervals. The logging script measured the ambient (Tamb), lid (Tlid) and junction (TSENSE0) temperatures every ten seconds as well, resulting in [Figure 5-6](#).

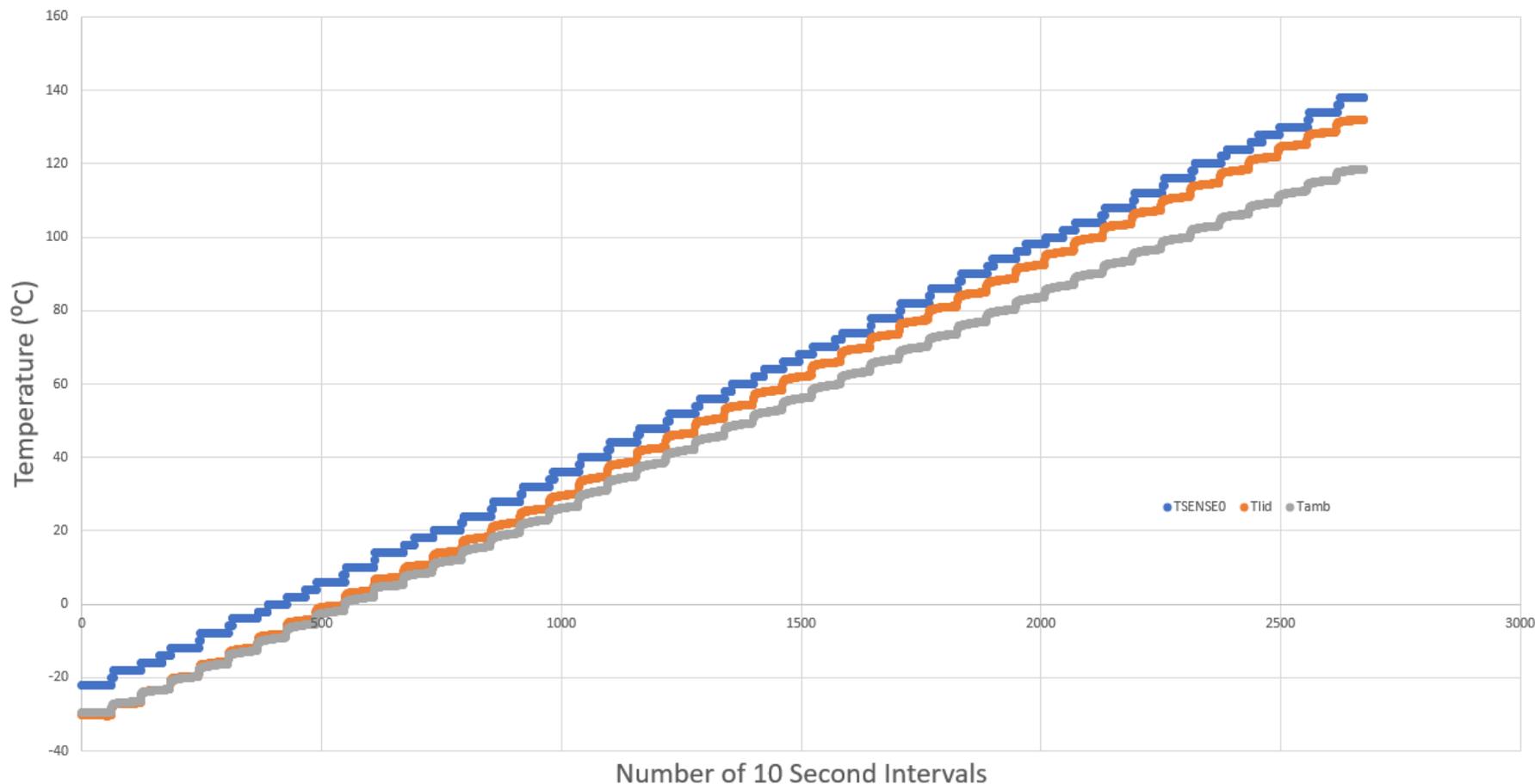


Figure 5-6. AM263x Control Card Temperatures with No Loading

Because the areas of the graph where the temperatures are climbing are not as important as the fully soaked temperatures, [Figure 5-7](#) and [Table 5-5](#) were created to more accurately represent the plateaued junction temperature readings for a given ambient temperature.

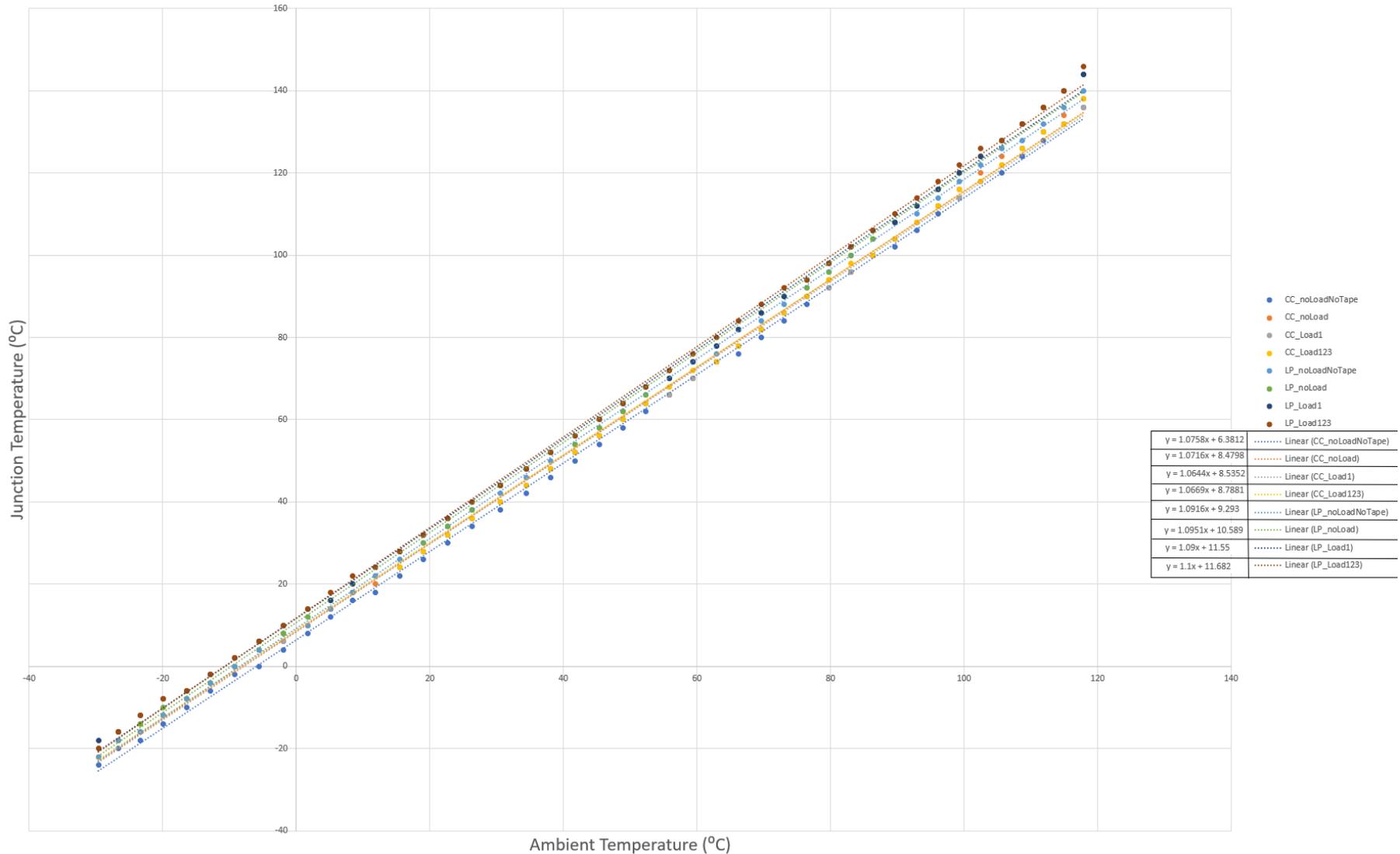


Figure 5-7. Junction Temperatures at Different Ambient Temperatures for AM263x Control Card and LaunchPad

Table 5-5. Measured values of Ambient and Junction Temperatures

ThermalAir Output (°C)	Ambient Temp. (°C)	TMDSNCND263 Junction Temperature at TSENSE0				LP-AM263 Junction Temperature at TSENSE0			
		No Loading No Kapton Tape (°C)	No Loading (°C)	Loading Core 1 (°C)	Loading Core 1/2/3 (°C)	No Loading No Kapton Tape (°C)	No Loading (°C)	Loading Core 1 (°C)	Loading Core 1/2/3 (°C)
-50	-29.6	-24	-22	-22	-22	-22	-20	-18	-20
-45	-26.6	-20	-18	-18	-18	-18	-16	-16	-16
-40	-23.3	-18	-14	-16	-14	-16	-14	-12	-12
-35	-19.9	-14	-12	-12	-12	-12	-10	-8	-8
-30	-16.4	-10	-8	-8	-8	-8	-6	-6	-6
-25	-12.9	-6	-4	-4	-4	-4	-2	-2	-2
-20	-9.3	-2	0	0	0	0	2	2	2
-15	-5.5	0	4	4	4	4	6	6	6
-10	-1.9	4	6	6	8	8	8	10	10
-5	1.7	8	10	10	10	10	12	14	14
0	5.1	12	14	14	14	14	16	16	18
5	8.4	16	18	18	18	18	20	20	22
10	11.9	18	20	22	22	22	24	24	24
15	15.4	22	24	24	24	26	28	28	28
20	19.0	26	28	28	28	30	30	32	32
25	22.7	30	32	32	32	34	34	36	36
30	26.3	34	36	36	36	38	38	40	40
35	30.6	38	40	40	40	42	44	44	44
40	34.4	42	44	44	44	46	48	48	48
45	38.1	46	48	48	48	50	52	52	52
50	41.8	50	52	52	52	54	54	56	56
55	45.4	54	56	56	56	58	58	60	60
60	48.9	58	60	60	60	62	62	64	64
65	52.4	62	64	64	64	66	66	68	68
70	55.9	66	66	66	68	70	70	70	72
75	59.4	70	70	70	72	74	74	74	76
80	62.9	74	74	74	74	76	78	78	80
85	66.2	76	78	78	78	82	82	82	84
90	69.7	80	82	82	82	84	86	86	88
95	73.0	84	86	86	86	88	90	90	92
100	76.4	88	90	90	90	92	92	94	94
105	79.8	92	94	92	94	96	96	98	98
110	83.1	96	96	96	98	100	100	102	102
115	86.4	100	100	100	100	104	104	106	106
120	89.6	102	104	104	104	108	108	108	110
125	92.9	106	108	108	108	110	112	112	114
130	96.1	110	112	112	112	114	116	116	118
135	99.3	114	116	114	116	118	120	120	122
140	102.5	118	120	118	118	122	124	124	126
145	105.6	120	124	122	122	126	128	128	128

Table 5-5. Measured values of Ambient and Junction Temperatures (continued)

ThermalAir Output (°C)	Ambient Temp. (°C)	TMDSNCD263 Junction Temperature at TSENSE0				LP-AM263 Junction Temperature at TSENSE0			
		No Loading No Kapton Tape (°C)	No Loading (°C)	Loading Core 1 (°C)	Loading Core 1/2/3 (°C)	No Loading No Kapton Tape (°C)	No Loading (°C)	Loading Core 1 (°C)	Loading Core 1/2/3 (°C)
150	108.7	124	126	126	126	128	132	132	132
155	111.9	128	130	130	130	132	136	136	136
160	115.0	132	134	132	132	136	140	140	140
165	117.9	136	138	136	138	140	144	144	146

5.4.5 Calculated Junction Temperature at Ambient Temperature Extremes

The measurements that were recorded for this procedure, only account for an ambient temperature range of approximately -30°C to 130°C due to the limitations of the testing environment as described in [Section 5.1](#). The trendlines of [Figure 5-7](#) can be used to extrapolate out the data to approximately calculate the junction temperature in a given configuration of the board, R5 core utilization, and ambient temperature.

[Table 5-6](#) shows the trendlines for junction temperature for different configurations as they relate to ambient temperature.

Table 5-6. Trendlines for Approximate Temperature Readings

Configuration	Junction Temperature Trendline Equation
CC only logging script with no Kapton tape on SoC	$y = 1.0758(x) + 6.3812$
CC only logging script	$y = 1.0716(x) + 8.4798$
CC logging script + Load Core 1	$y = 1.0644(x) + 8.5352$
CC logging script + Load Cores 1,2,3	$y = 1.0669(x) + 8.7881$
LP only logging script with no Kapton tape on SoC	$y = 1.0916(x) + 9.293$
LP only logging script	$y = 1.0951(x) + 10.589$
LP logging script + Load Core 1	$y = 1.09(x) + 11.55$
LP logging script + Load Cores 1,2,3	$y = 1.1(x) + 11.682$

Junction temperature can be approximate for ambient temperature extremes such as 125°C by plugging in 125 into any of the [Table 5-6](#) equations. For example, an AM263x LaunchPad at full utilization can be represented by the equation $y = 1.1(x) + 11.682$. Therefore, an LP-AM263x at full R5 core utilization with an ambient temperature of 125 °C has a junction temperature of approximately 149.18 °C.

AM263x junction temperature approximations for ambient temperature extremes have been calculated using the trendline equations and are shown in [Table 5-7](#).

Table 5-7. Approximate Junction Temperatures at Ambient Temperature Extremes

Measurement	Approximate Junction Temperature at -40°C Ambient	Approximate Junction Temperature at 125°C Ambient
CC only logging script with no Kapton tape on SoC	-36.65 °C	140.86 °C
CC only logging script	-34.38 °C	142.43 °C
CC logging script + Load Core 1	-34.04 °C	141.59 °C
CC logging script + Load Cores 1,2,3	-33.89 °C	142.15 °C
LP only logging script with no Kapton tape on SoC	-34.37 °C	145.74 °C
LP only logging script	-33.21 °C	147.48 °C
LP logging script + Load Core 1	-32.05 °C	147.80 °C
LP logging script + Load Cores 1,2,3	-32.32 °C	149.18 °C

As predicted in the [EVM Comparison chapter](#), The AM263x Control Card has a better thermal performance due to the increased number of ground layers. For a complete list of best practices and rules of thumb when designing a PCB for the best thermal performance, see the [Section 4](#).

6 Using the Thermal Model

Thermal modeling software such as MentorGraphics Flotherm or ANSYS ICEPAK is used to open the model and build the thermal environment for simulation. The software allows you to build out entire situations and edge cases to estimate thermal performance. The simulation can also be as simple or as detailed as the user requires. For example, an SoC's thermal performance could be simulated using a simple JEDEC-defined 2S2P (two metal planes and two signal layers) test board. The Package thermal characteristics section of a Sitara microcontroller device data sheet has values that are based on a 2S2P system.

To import a device's characteristics into simulation, a thermal model is required. The SoC thermal model is available for all Sitara microcontrollers in the form of an Electronics Cooling XML (ECXML) file. This file type is established by JEDEC as the standard for exchanging electronic thermal system level simulation models to end users. The thermal model provides an accurate representation of the entire SoC design and, therefore, an accurate representation of junction and lid temperature. The thermal model still requires additional configuration and setup in the simulation software to provide the best approximation of a system's thermal profile.

For the best thermal simulation results, the PCB design should be imported into the simulation software as well as the enclosure and airflow properties. Additionally, the device-specific Power Estimation Tool should be used to estimate the operating power of the SoC during operation. The estimated operating power can then be used with the thermal model for an even more accurate representation of the thermal profile.

Figure 6-1 shows the flow for building an accurate system for thermal modeling.

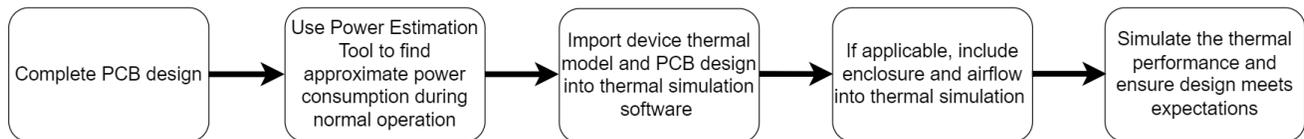


Figure 6-1. Thermal Simulation Flow

7 References

In addition to this document, the following references are available for download at www.ti.com.

- [AM2634 Sitara™ Microcontrollers](#)
- [AM263x Hardware Design Guide](#)
- [AM263x Sitara™ Microcontrollers Data Sheet](#)
- [AM263x Sitara™ Microcontrollers Technical Reference Manual](#)
- [AM263x Sitara™ Microcontrollers Silicon Errata](#)
- [LP-AM263 Tool Page](#)
- [TMDSCNCD263 Tool Page](#)

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