Intel® Pentium® 4 Processor In the 423-pin Package Thermal Design Guidelines

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1 INTRODUCTION

In a system environment, the processor's temperature is a function of both the system and component thermal characteristics. The system level thermal constraints consist of the local ambient temperature at the processor and the airflow over the processor as well as the physical constraints at and above the processor. The processor's temperature depends on the component power dissipation, size and material (effective thermal conductivity) of the integrated heat spreader, and the presence of a thermal cooling solution.

All of these parameters are aggravated by the continued push of technology to increase performance levels (higher operating speeds, MHz) and packaging density (more transistors). As operating frequencies increase and packaging size decreases, the power density increases and the thermal cooling solution space and airflow become more constrained. The result is an increased importance on system design to ensure that thermal design requirements are met for each component in the system.

All dimensions in this document, unless otherwise noted, are in inches.

1.1 Document Goals

The thermal power of the Pentium® 4 processor generation is higher, as well as denser, than previous Intel architecture processors. Depending on the type of system and the chassis characteristics, new system designs may be required to provide adequate cooling for the processor. The goal of this document is to provide an understanding of these thermal characteristics and discuss guidelines for meeting the thermal specifications.

1.2 Document Scope

This document discusses thermal management techniques for the Pentium 4 processor, which is primarily intended for the performance desktop segment. It will also address the issues of the integrated thermal management logic and its impact on thermal design.

The physical dimensions and power numbers used in this document are for reference only. Please refer to the *Pentium 4 processor in the 423-pin Package Datasheet* for the product dimensions, thermal power dissipation and maximum case temperature. In case of conflict, the data in the Datasheet supercedes any data in this document.

1.3 References

- *Pentium 4 processor in the PGA423 Package Datasheet*
- *IA32 Intel Architecture Software Developer Manuals Volumes 1-3*
- *Pentium 4 processor and Intel® 850 Chipset Platform Design Guidelines*
- *423 Pin Socket (PGA423) Design Guidelines*

For details on ordering this documentation, contact your Intel field sales representative or visit the Intel web site http://developer.intel.com/.

1.4 Definition of Terms

- T_{LA} - the measured ambient temperature locally surrounding the processor. The ambient temperature should be measured just "upstream" of a passive heat sink, or at the fan inlet for an active heat sink (see Figure 7).
- $T_{AMBIENT-OEM}$ - the target worst-case ambient temperature at a given **external** system location as defined by the system designer (OEM).

- $T_{AMBIENT\text{-}EXTERNAL}$ - the measured ambient temperature at the OEM defined **external** system location.
- $T_{AMBIENT\text{-}MAX}$ - the target worst-case local ambient temperature. This can be determined by placing the system in maximum external temperature conditions and measuring the ambient temperature locally surrounding the processor. Under these conditions, $T_{LA} = T_{AMBIENT\text{-}MAX}$.
- $T_{CASE\text{-}MAX}$ - the maximum allowed case temperature of the Pentium 4 processor, as specified in the processor datasheet.
- T_{CASE} - the measured case temperature of the Pentium® 4 processor.
- TIM - Thermal Interface Material – The thermally conductive compound between the heat sink and the processor case. This material fills the air gaps and voids, and enhances the spreading of the heat from the case to the heat sink.
- θ_{TIM} - The thermal resistance of the thermal interface material. Also referred to as "theta case to sink".
- θ_{SA} - The thermal resistance between the heat sink base and the ambient air. This is defined and controlled by the system thermal solution. Also referred to as " theta sink to ambient".
- θ_{CA} - The thermal resistance between the processor's case and the ambient air. This is defined and controlled by the system thermal solution. Also referred to as "theta case to ambient", it includes both θ_{CS} and θ_{SA}.
- P_{MAX} - the maximum processor power, as specified in the processor's datasheet.
- 423 Pin Socket - The through-hole mount Zero Insertion Force (ZIF) socket designed to accept the Pentium 4 processor.
- ACPI - Advanced Configuration and Power Interface (See http://www.teleport.com/~acpi/)
- Bypass - Bypass is the area between a heat sink and any object that can act to form a duct. For this example it can be expressed as a dimension away from the outside dimension of the fins to the nearest surface.
- Thermal Monitor - The Pentium 4 processor implements new thermal management features consisting of: an on-die thermal diode, external bus signal, thermal control circuit and processor registers to assist with managing thermal control of the processor.
- Thermal Control Circuit - The portion of Thermal Monitor, which modulates the clocks during an over-temperature event.
- Thermal Design Point (TDP) – Processor thermal solutions should be designed to meet the TDP as listed in the *Pentium 4 processor in the 423 pin Package Datasheet.*

1.5 Revision History

Date of Release	Revision No.	Description
May 1999	0.5	Initial release of document
November 1999	0.6	Updated mechanical drawings. Updated thermal management discussion
January 2000	1.0	Updated mechanical drawings. Updated thermal metrology section
May 2000	1.1	Updated mechanical drawings. Added thermal test software discussion
November 2000	2.0	Final release.

2 IMPORTANCE OF THERMAL MANAGEMENT

The objective of thermal management is to ensure that the temperatures of all components in a system are maintained within functional limits. The functional temperature limit is the range within which the electrical circuits can be expected to meet their specified performance requirements. Operation outside the functional limit can degrade system performance, cause logic errors or cause component and/or system damage. Temperatures exceeding the maximum operating limits may result in irreversible changes in the operating characteristics of the component.

3 PENTIUM 4 PROCESSOR PACKAGING TECHNOLOGY

The Pentium® 4 processor is available in Pin Grid Array (PGA) packaging. The Integrated Heat Spreader (IHS) is the interface between the processor silicon and a heat sink. The processor connects to the motherboard through a ZIF through-hole socket. A description of the socket can be found in the *423 Pin Socket (PGA423) Design Guidelines.*

Package dimensions of the Pentium 4 processor are shown in Figure 1.

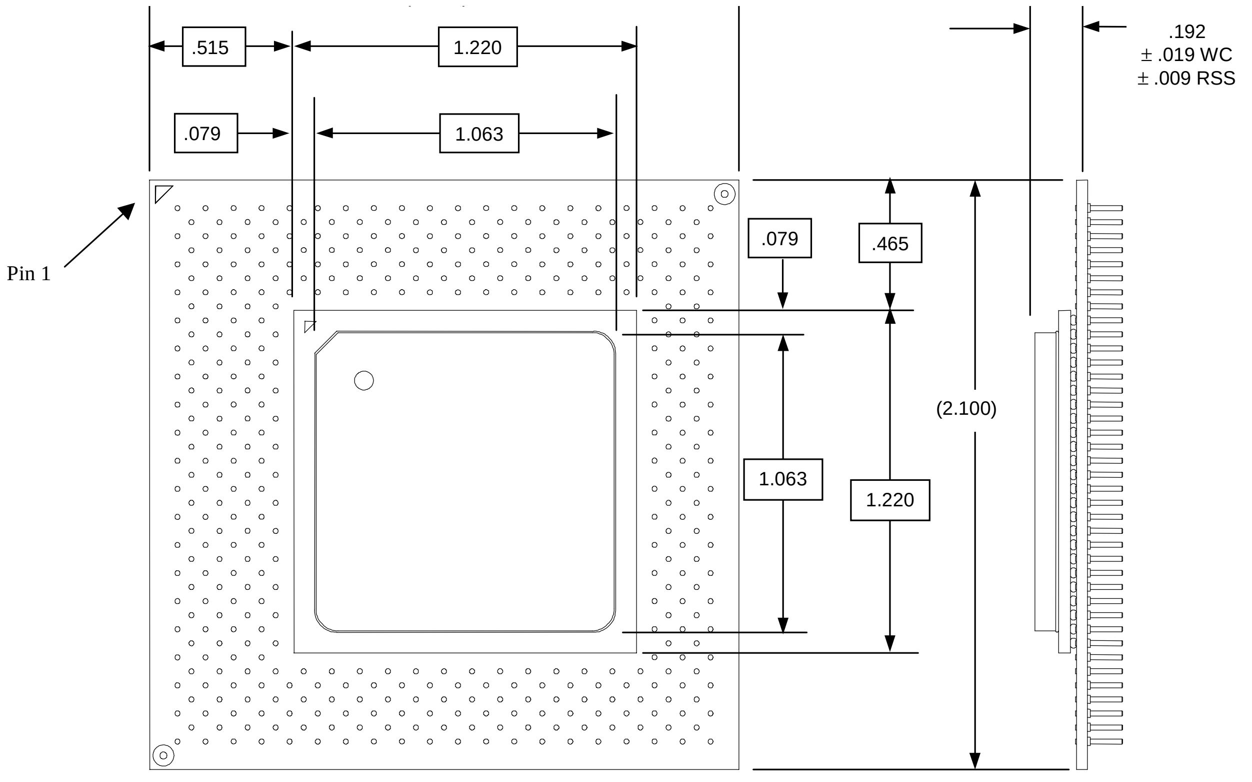


Figure 1. Pentium 4 processor package dimensions

Note: In case of conflicts in dimensions the processor datasheet supercedes this document.
All dimensions are in inches

4 THERMAL SPECIFICATIONS

Refer to the *Pentium 4 processor in the 423-pin Package Datasheet*, for the thermal specifications of the Pentium 4 processor.

In order to ease the burden on chassis cooling solutions a new Thermal Monitor feature has been integrated into the silicon of the Pentium® 4 processor. By taking advantage of the Thermal Monitor feature, system designers may reduce the cooling system cost while maintaining the processor reliability and performance goals. Other options within the thermal management logic allow system software to monitor and control the thermal characteristics of the processor. Implementation options and recommendations are described in Section 8.

4.1 Assumptions

For the purposes of this design guideline, the following reliability and operation assumptions have been made about the processor:

- Considering the power dissipation levels and typical system ambient environments of 35°C to 45°C, the processor's temperature cannot be maintained at or below the specified guidelines without additional thermal enhancement to dissipate the heat generated by the processor. In other words, a heat sink is required.
- The thermal characterization data described in later sections illustrates that both a thermal-cooling device and system airflow is needed. The size and type (passive or active) of thermal cooling device and the amount of system airflow are related and can be traded off against each other to meet specific system design constraints. In typical systems, board layout, spacing, and component placement limit the thermal solution size. Airflow is determined by the size and number of fans, along with their placement in relation to the components and the airflow channels within the system. In addition, acoustic noise constraints may limit the size, number, and types of fans that can be used in a particular design.

To develop a reliable, cost-effective thermal solution, all of the above variables must be considered. Thermal characterization and simulation should be carried out at the entire system level accounting for the thermal requirements of each component.

4.2 Processor Case Temperature

The Integrated Heat Spreader (IHS) is intended to provide the common interface and attach location for all thermal solutions. The IHS acts to spread the concentrated heat from the core to a larger surface area, which will allow a more efficient heat transfer to the heat sink. Thermal solutions can be active or passive. Active solutions incorporate a fan in the heat sink and may be smaller than a passive heat sink. Passive thermal solutions do not incorporate a fan in the heat sink. Considerations in heat sink design include:

- Local ambient temperature at the heat sink
- Surface area of the heat sink
- Volume of airflow over the heat sink surface area
- Power being dissipated by the processor
- Physical volumetric constraints placed by the system

Techniques for measuring case temperatures are provided in Section 7.1.4.1.

4.3 Processor Power

The processor power, as listed in the Dataheet, is the total thermal design power that is dissipated through the IHS.

5 DESIGNING FOR THERMAL PERFORMANCE

In designing for thermal performance, the goal is to keep the processor within the operational thermal specifications. Failure to do so will shorten the life of the processor and potentially cause erratic system behavior. The thermal design is required to ensure these operational thermal specifications are maintained. The heat generated by components within the chassis must be removed to provide an adequate operating environment for both the processor and other system components. Moving air through the chassis transports the heat generated by the processor and other system components out of the system, while bringing in air from the external ambient environment.

5.1 Airflow Management

It is important to manage the amount of air that flows within the system, as well as how it flows, to maximize the amount of cool air that flows over the processor. System airflow can be increased by adding one or more fans to the system, or by increasing the output (increasing the speed or size) of an existing system fan(s). Managing the airflow direction using baffles or ducts can also increase local airflow. Heating effects from chipset, voltage regulators, add-in boards, memory, and disk drives greatly reduce the cooling efficiency of this air, as does re-circulation of warm interior air through the system fan. Care must be taken to minimize the heating effects of other system components, and to eliminate warm air re-circulation.

If no air path exists across the processor, the warm air from the processor will not be removed from the system, resulting in localized heating ("hot spots") around the processor. Heat sink fins passive thermal solution designs should be aligned with the direction of airflow. If the airflow is horizontal the fins should be oriented horizontally. Similarly, for a vertical airflow, the heat sink fins should be oriented vertically.

Figure 2 shows two examples of air exchange through a PC style chassis. The system on the left is an example of good air exchange incorporating both the power supply fan as well as an additional system fan. The system on the right shows a poorly vented system using only the power supply fan to move the air, resulting in inadequate airflow.

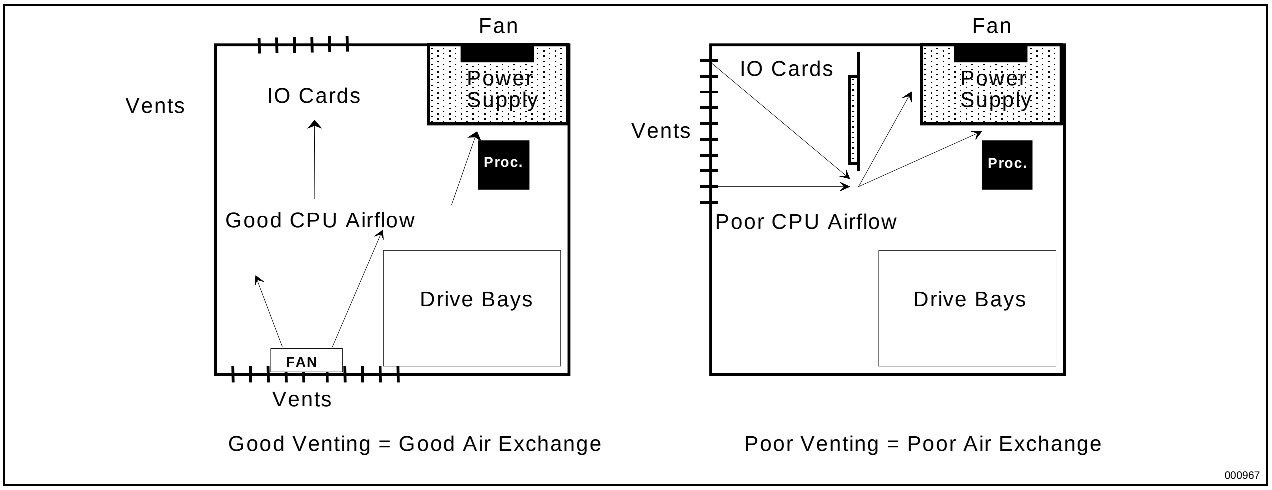


Figure 2. Example of Air Exchange through a PC Chassis

5.2 Bypass

Bypass is the distance around the heat sink where air may travel without passing through the fins of the heat sink. A heat sink will have infinite bypass if it is sitting in free space. A heat sink which has a duct or other devices surrounding it which are 0.2” (5.1mm) away from the outer edges of the heat sink has a bypass of 0.2” (5.1mm). A smaller bypass forces more air to pass through the fins of the heat sink, rather than around the heat sink. This is especially important as the heat sink fin density increases. The higher the fin density, the more resistance the heat sink poses to the air and the more likely the air will travel around the heat sink instead of through it unless the bypass is small. Air traveling around the heat sink, rather than through, will have little affect on cooling the processor.

5.3 Heat Sink Solutions

One method of improving thermal performance is to increase the surface area of a device by attaching a metallic heat sink. To maximize the heat transfer, the thermal resistance from the heat sink to the air can be reduced by maximizing the airflow through the heat sink fins as well as by maximizing the surface area of the heat sink itself.

5.4 Pentium 4 processor Reference Heat Sink

Intel is enabling a reference heat sink for the Pentium® 4 processor. This active heat sink design includes a 60 mm fan and is designed assuming a T_{LA} of 45ºC and sufficient cross flow to maintain the local ambient temperature.

In order to maximize longevity, a heat sink consisting of folded aluminum fins brazed to a copper base has been designed. The copper base provides increased heat spreading and the folded fins provide greater surface area for thermal dissipation.

5.4.1 Heat Sink Weight

The heat sink attachment requires a retention mechanism. Heat sinks that attach to the reference retention mechanism should not exceed 450 grams. These are the design limits for the motherboard components, heat sink retention mechanism, heat sink attach clips, and 423 pin socket to withstand mechanical shock and vibration.

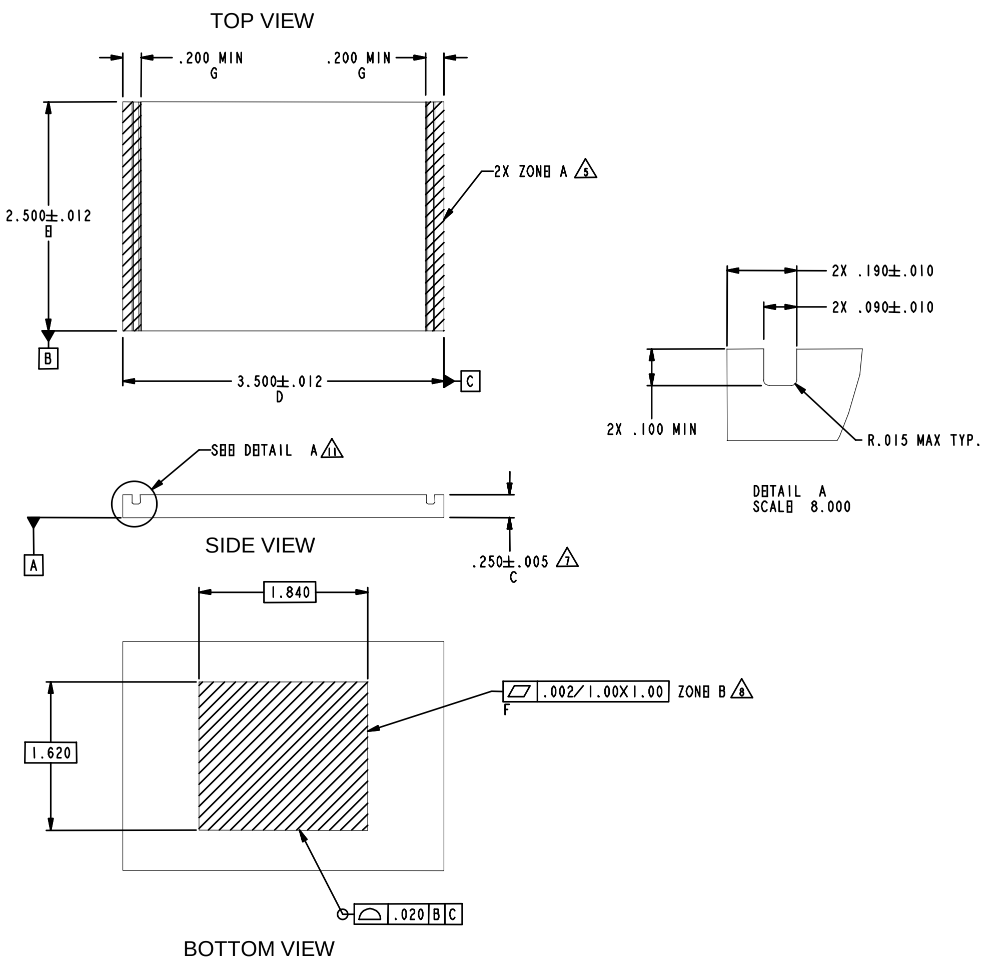
The test limits for vibration are 10min/axis, 3 axes over a frequency range of 5Hz to 500Hz. This results in a Power Spectral Density (PSD) of 3.13g RMS. The system level shock design limits are 30G trapezoidal, 11 ms duration, 170 in./sec minimum velocity change applied 3 times in the + and – directions in each of 3 perpendicular axes.

5.4.2 Altitude

The reference heat sink solutions will be evaluated at sea level. In general the performance drops by about 0.5-1.0 ºC per 1000 feet of elevation. The system designer needs to account for this in the overall system thermal design.

5.4.3 Heat Sink Mechanical Envelope

The following two figures show the critical to function (CTF) and maximum heat sink dimensions for the reference heat sink design intended for the reference retention mechanism. Figure 3 shows the dimension and “keep-in” for the heat sink base, while Figure 4 shows the maximum heat sink dimensions.



NOTES

4 ALL DISPLAYED DIMENSIONS ARE CRITICAL TO FUNCTION.

5 THE FIN STRUCTURE ASSEMBLED TO THE TOP SURFACE OF THE BASE MAY NOT INTRUDE ON ZONE A.

6 DATUM A IS DEFINED AS THE BOTTOM OF THE PART.

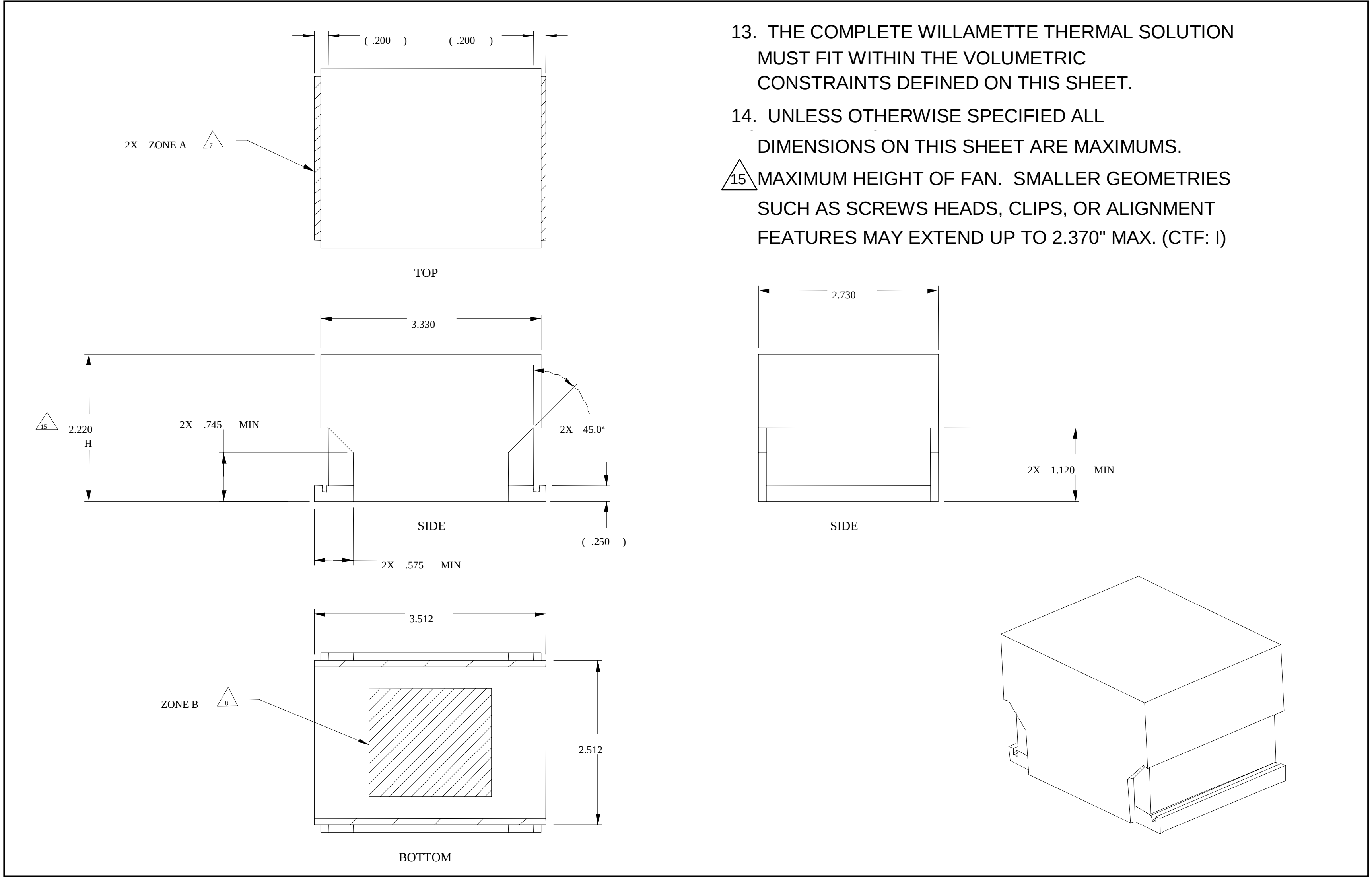
7 THIS THICKNESS MUST BE MAINTAINED BETWEEN ZONE A AND DATUM A.

8 FLATNESS ZONE B IS REQUIRED FOR PROCESSOR REFERENCING AND THERMAL INTERFACE APPLICATION.

9 LETTERS ATTACHED TO DIMENSIONS ARE FOR CRITICAL TO FUNCTION DIMENSION TRACKING.

11 SLOT DOES NOT HAVE TO TRAVERSE ENTIRE 2.500” LENGTH. IT MAY BE LOCALIZED, CENTERED ON DATUM B, 1.000” IN LENGTH.

Figure 3. Heat Sink Base Dimensions



13. THE COMPLETE WILLAMETTE THERMAL SOLUTION MUST FIT WITHIN THE VOLUMETRIC CONSTRAINTS DEFINED ON THIS SHEET.

14. UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ON THIS SHEET ARE MAXIMUMS.

15 MAXIMUM HEIGHT OF FAN. SMALLER GEOMETRIES SUCH AS SCREWS HEADS, CLIPS, OR ALIGNMENT FEATURES MAY EXTEND UP TO 2.370" MAX. (CTF: I)

Figure 4. Heat Sink with Enabled Retention Mechanism

5.5 Thermal Interface Management

To optimize the heat sink design for the Pentium® 4 processor, it is important to understand the impact of factors related to the interface between the processor and the heat sink. Specifically, the bond line thickness, interface material area and interface material thermal conductivity should be selected to realize the most effective thermal solution.

5.5.1 Bond Line Management

Any gap between the processor's heat spreader and the heat sink base will degrade thermal solution performance. The larger the gap between the two surfaces, the greater the thermal resistance. The thickness of the gap is determined by the flatness of both the heat sink base and the integrated heat spreader, plus the thickness of the thermal interface material (i.e. thermal grease) used between these two surfaces and the clamping force applied by the heat sink attach clip(s).

5.5.2 Interface Material Area

The size of the contact area between the processor and the heat sink base will impact the thermal resistance. There is, however, a point of diminishing returns. Unrestrained incremental increases in thermal interface material area do not translate to a measurable improvement in thermal performance. The Pentium 4 processor in the 31mm package has an IHS surface area of 1.13 square inches (7.29 sq. cm).

5.5.3 Interface Material Performance

Two factors impact the performance of the interface material between the processor and the heat sink base:

1. Thermal resistance of the material
2. Wetting/filling characteristics of the material

Thermal resistance is a description of the ability of the thermal interface material to transfer heat from one surface to another. The higher the thermal resistance, the less efficient the material is at transferring heat. The thermal resistance of the interface material has a significant impact on thermal performance. The higher the thermal resistance, the larger the temperature drop is across the interface and the more efficient the thermal solution (i.e. heat sink) must be to achieve the desired cooling.

The wetting or filling characteristic of the thermal interface material is its ability, under the load applied by the heat sink attach clips, to spread and fill the gap between the processor and the heat sink. Since air is an extremely poor thermal conductor, the more completely the interface material fills the gaps, the lower the temperature drop across the interface. In this case, thermal interface material area also becomes significant; the larger the desired thermal interface material area, the higher the force required to spread the thermal interface material.

Intel has determined through thermal characterization that it may be challenging to meet the thermal performance targets with the use of Phase Change thermal interface materials. The use of Thermal Grease in conjunction with high performance heat sink technologies (e.g. copper base folded fin or high aspect ratio extruded aluminum with high performance attached fans) has been demonstrated to meet the thermal performance requirements.
The use of thermal grease is recommended. Intel's thermal solution reference designs uses ShinEtsu* G749 Thermal Grease.

Intel has determined through mechanical characterization that the use of phase change thermal interface materials may lead to motherboard, processor, and /or surface mount component damage in mechanical shock or mechanical drop testing. Phase change thermal interface materials create a strong adhesive bond between the processor package and heat sink that can lead to large deflections and high stresses. The damage induced may not be readily detectable.

5.6 Fans

Fans are needed to move the air through the chassis. The acoustic noise level of a fan is usually related to the speed of the fan as well as the number and shape of the fan blades.. Maximum acceptable noise levels may limit the fan output or the number of fans selected for a system. The enabled reference design for the Pentium® 4 processor incorporates a fan into the heat sink.

5.6.1 Placement

Proper placement of the fans can help ensure that the processor is being properly cooled. Because of the difficulty in building, measuring and modifying a mechanical assembly, models are typically developed. A well designed model can be used to simulate a proposed solution for thermal effectiveness to determine the optimum location for fans and vents within a chassis. Prototype assemblies can also be built and tested to verify that the system components and processor thermal specifications are met.

An intake air fan ideally is centered vertically and placed along one axis with respect to the processor and passive heat sink. The fan should also be approximately 2 inches from the leading edge of the heat sink. Figure 5 shows the typical fan placement for an ATX form factor chassis.

With an active fan heat sink, such as the enabled reference heat sink design, the critical function of the system fan is to provide sufficient amounts of cool air to the heat sink fan inlet and push the exhaust air away to minimize re-circulation.

The system fans should be pulling in air from the exterior of the system, which flows directly toward the heat sink. By reducing the preheating of the air flowing into the heat sink fan, a 1°C for 1°C reduction in processor case temperature can be achieved with all other parameters remaining constant.

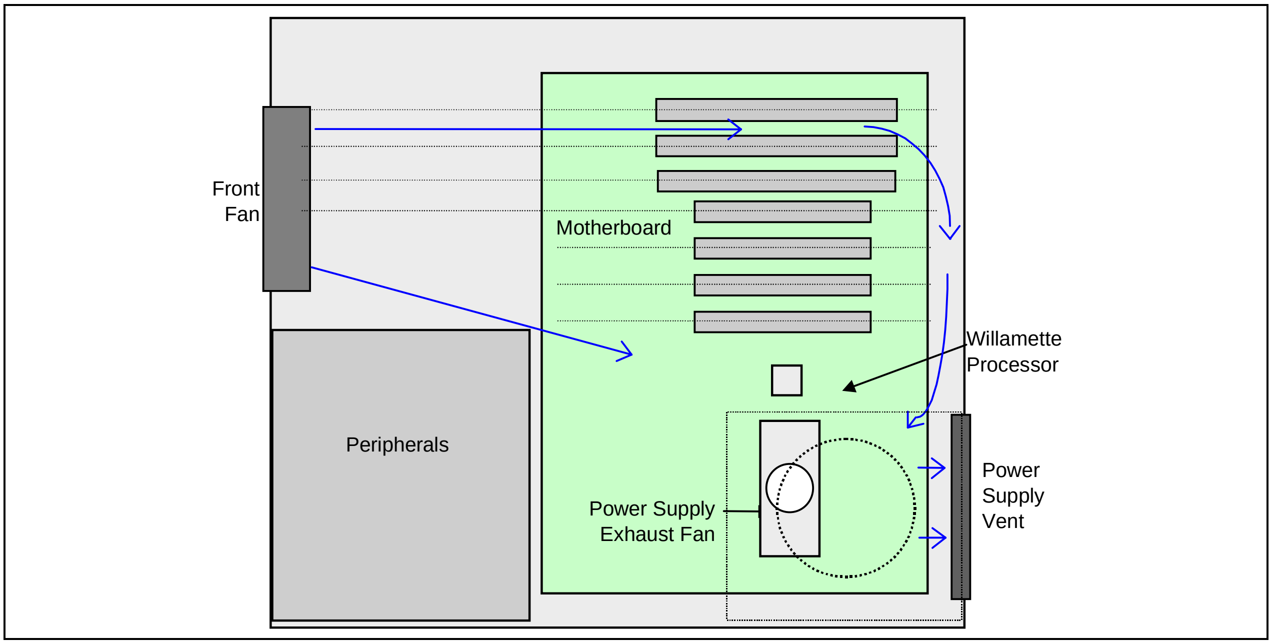


Figure 5. Fan Placement and Layout of an ATX Form Factor Chassis – Top View

5.6.2 Direction

For passive cooling solutions, if the fan(s) is (are) not moving air through the heat sink, then little cooling can occur and the processor may operate above the specified temperature. Two possibilities exist for blowing air through the heat sink of a Pentium® 4 processor. Air can be blown horizontally, parallel to the baseboard, which blows the air through the length of the heat sink. Alternatively the air stream can be blown vertically, perpendicular to the baseboard, or down into the heat sink. This will depend on the layout of other components on the board and/or within the chassis. Preferably the intake fan will blow through the heat sink lengthwise. In this case, it may be possible for the heat sink fins to be shorter (z – axis). Both of these factors are considerations when laying out components on the board and in the chassis.

The direction of the chassis airflow can be modified with baffles or ducts to direct the airflow toward the processor. This will increase the local flow through the processor heat sink and may eliminate the need for a second, larger, or higher speed fan. Baffles and ducts can also provide air to the heat sink without the preheating caused by other system components

5.6.3 Size And Quantity

It does not necessarily hold true that the larger the fan the more air it blows. A small blower or axial fan using ducting might direct more air through the heat sink than a large axial fan blowing non-directed air toward the heat sink. The following provide some guidelines for size and quantity of the fan(s).

The system fan should be a minimum of 80 mm (3.150") square, with a minimum airflow of approximately 200 LFM (linear feet per minute). Ideally two (2) fans should be used. The intake air fan would blow cool air directly toward the processor and heat sink assembly, while a second fan, possibly in the power supply would exhaust the hot air out of the system.

5.6.4 Venting

Intake venting should be placed at the front (user side) of the system to avoid any re-circulation that can occur from the rear of a system with little wall clearance. Location should be selected with consideration for cooling of processor and peripherals (drives and add-in cards). Intake venting directly in front of the intake fan is the most optimal location. The ideal design will provide airflow directly through the processor heat sink.

5.6.4.1 Placement

Exhaust venting in conjunction with the power supply exhaust fan is usually sufficient for smaller systems. However, depending on the number, location and types of add-in cards, exhaust venting may be necessary near the adapter cards. This should be modeled or prototyped for the optimum thermal potential. Hence, a system should be modeled for the worst case; i.e. all expansion slots should be occupied with add-in options.

5.6.4.2 Area and/or Size

The area and/or size of the intake vents should consider the size and shape of the fan(s). Adequate air volume must be obtained and thus will require adequate sized vents. Intake vents should be located in front of the intake fan(s) and adjacent to the drive bays. Venting should be approximately 50% to 60% open in the EMI (Electro-Magnetic Interference) containment area. Outside the EMI (Electro-magnetic Interference) containment area, the open percentage can be greater if needed for aesthetic appeal (i.e., bezel/cosmetics). Caution should be exercised that venting is not excessive or poorly placed which can cause re-circulation of warm exhaust air.

5.6.4.3 Vent Shape

Round, staggered pattern openings are best for EMI containment, acoustics and airflow balance.

6 ALTERNATIVE COOLING SOLUTIONS

In addition to passive heat sink, fan heat sinks and system fans, other solutions exist for cooling integrated circuit devices. For example, ducted blowers, heat pipes and liquid cooling are all capable of dissipating additional heat. Due to their varying attributes, each of these solutions may be appropriate for a particular system implementation. More information on this topic can be located on Intel's web site at http://developer.intel.com/.

6.1 Ducting

Ducts can be designed to isolate the processor from the effects of system heating (such as add-in cards), and to maximize the processor cooling temperature budget. Typical temperature rise from external ambient to the local ambient near the processor can be greater than 10^{o}C. Air provided by a fan or blower can be channeled to the processor and heat sink with little or no rise from the external ambient temperature.

6.1.1 Ducting Placement

When ducting is to be used, it should direct the airflow evenly from the fan through the length of the heat sink. This should be accomplished, if possible, with smooth, gradual turns, as this will enhance the airflow characteristics. Sharp turns in ducting should be avoided as they increase friction, drag, and pressure drop and will greatly reduce the volume of air reaching the processor heat sink.

6.2 System Components

6.2.1 Placement

Peripherals such as CD-ROMs, floppy drives, hard drives, VR/M (voltage regulators/modules), etc. can be placed to take advantage of a fan's movement of ambient air (by placing them near intake or exhaust fans or venting). Some add-in cards often have a low tolerance for temperature rise. These components should be placed near additional venting if they are downstream of the processor to minimize an increase in their ambient temperature.

6.2.2 Power

Some types of drives, such as floppy drives, do not dissipate much heat, while others (e.g. read/write CD-ROM drives, SCSI drives) dissipate a great deal of heat. These hotter components should be placed near fans and/or venting whenever possible. The same can be said for some types of add-in cards. Some PCI cards are very low wattage (approximately 5W) while others can be as high as 25W, per the PCI specification. AGP graphics devices can dissipate up to 25W per the AGP revision 2.0 specifications while AGP Pro50 devices dissipate 25-50W and AGP Pro110 devices dissipate 50-110W per AGP Pro revision 1.1a specifications. Great care should be taken to ensure that these cards have sufficient cooling, while not adversely affecting the processor cooling.

6.2.3 Voltage Regulation Module (VRM) Considerations

Voltage regulation module (VRM) designs must also be considered in system cooling solutions. Because proper power delivery to the processor demands that the VRM be placed very close to the processors, local ambient temperature for the VRM may be affected by the heating of the nearby processors. Thermal modeling of the system should therefore include the VRM in the simulation.

7 THERMAL METROLOGY

The following sections will discuss the techniques for testing thermal solutions. It should be noted that determining if a processor is sufficiently cooled is not as simple as it may seem. Carefully read the following instructions and interpretation steps to validate your cooling solution.

7.1 Thermal Metrology for Pentium® 4 processors

7.1.1 Thermal Resistance

The thermal resistance value from case-to-local ambient (Θ_{CA}) is used as a measure of the cooling solution's thermal performance. Thermal resistance is measured in units of °C/W. The thermal resistance of the case-to-local ambient, Θ_{CA}, is comprised of the Θ_{TIM} thermal interface material thermal resistance and the sink-to-local ambient thermal resistance (Θ_{SA}) Figure 6. This value Θ_{TIM}, is strongly dependent on the thermal conductivity and thickness of the TIM between the heat sink and surface of the processor.

Θ_{SA} is a measure of the thermal resistance from the bottom of the cooling solution to the local ambient air. Θ_{SA} is dependent on the heat sink's material, thermal conductivity and geometry, and is strongly dependent on the air velocity through the fins of the heat sink.

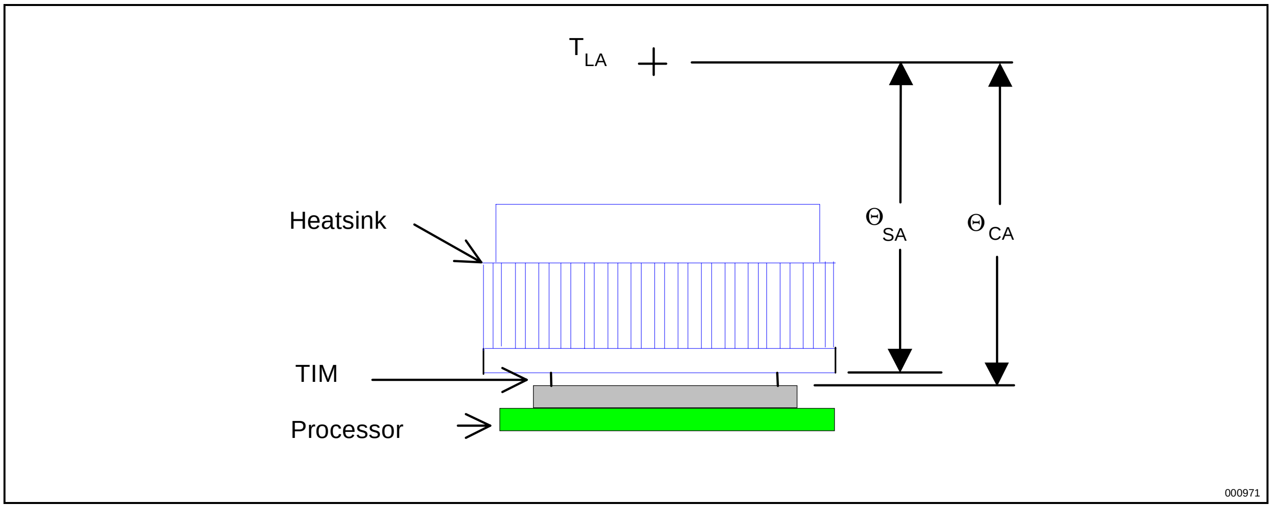


Figure 6. Thermal Resistance Relationships

The thermal parameters are related by the following equations:

Equation 1. Case to Ambient Thermal Resistance:

$$\Theta_{CA} = (T_{CASE} - T_{LA}) / P_D$$

Equation 2. Case to Ambient Thermal Resistance:

$$\Theta_{CA} = \Theta_{TIM} + \Theta_{SA}$$

Where:

Θ_{CA} = Thermal resistance from case-to-local ambient (°C/W)

T_{CASE} = Processor case temperature (°C)

T_{LA} = Local ambient temperature in chassis around processor (°C)

P_D = Processor power dissipation (W) (assume all power goes to the case)

Θ_{TIM} = Thermal resistance of the thermal interface material (°C/W)

Θ_{SA} = Thermal resistance from heat sink-to-local ambient (°C/W)

7.1.2 Thermal Solution Performance

All processor thermal solutions attach to the processor at the IHS. The system thermal solution must adequately control the local ambient air around the processor (T_{LA}). The lower the thermal resistance between the processor and the local ambient air, the more efficient the thermal solution. The required Θ_{CA} is dependent upon the maximum allowed processor temperature (T_{CASE}), the local ambient temperature (T_{LA}) and the processor power (P_D).

Use equations 1 and 2 to determine a target Θ_{CA} and Θ_{SA} using the following assumptions.

T_{CASE} = 75 °C, hypothetical maximum case temperature specification

T_{LA} = Assume 45°C, a typical value for desktop systems

P_D = Assume 62 W, hypothetical thermal design power (TDP)

Θ_{TIM} = Assume 0.15 °C/W, the target for the enabled solution

Solving for the equation 1 from above:

$$\Theta_{CA} = (T_{CASE} - T_{LA}) / P_D$$

$$= (75 - 45) / 62$$

$$= 0.48\ °C/W$$

Solving for equation 2 from above:

$$\Theta_{CA} = \Theta_{TIM} + \Theta_{SA}$$

$$\Theta_{SA} = \Theta_{CA} - \Theta_{TIM}$$

$$= 0.48 - 0.15$$

$$= 0.33\ °C/W$$

7.1.3 Local Ambient Temperature Measurement Guidelines

Local ambient temperature, T_{LA}, is the temperature of the ambient air surrounding the processor. In a system environment, ambient temperature is the temperature of the air upstream of the processor and in its close vicinity; or in an active cooling solution; it is the inlet air to the active cooling device.

It is worthwhile to determine the local ambient temperature in the chassis around the processor to better understand the effect it may have on the case temperature.

The following guidelines are meant to alleviate the non-uniform measurements found in typical systems. The local ambient temperature is best measured as an average of the localized air surrounding the processor. The following guidelines are meant to enable accurate determination of the localized air temperature around the processor during system thermal testing. These guidelines are meant as a reasonable expectation to ensure the product specifications are met.

1. During system thermal testing, a minimum of two thermocouples should be placed approximately 0.5 to 1.0 inches (12.7 to 25.4mm) away from processor and heat sink as shown in the Figure 7. This placement guideline is meant to minimize localized hot spots due to the processor, heat sink, or other system components.
2. The thermocouples should be placed approximately 2 inches (50.4mm) above the baseboard. This placement guideline is meant to minimize localized hot spots from baseboard components.
3. The T_{LA} should be the average of the thermocouple measurements during system thermal testing.

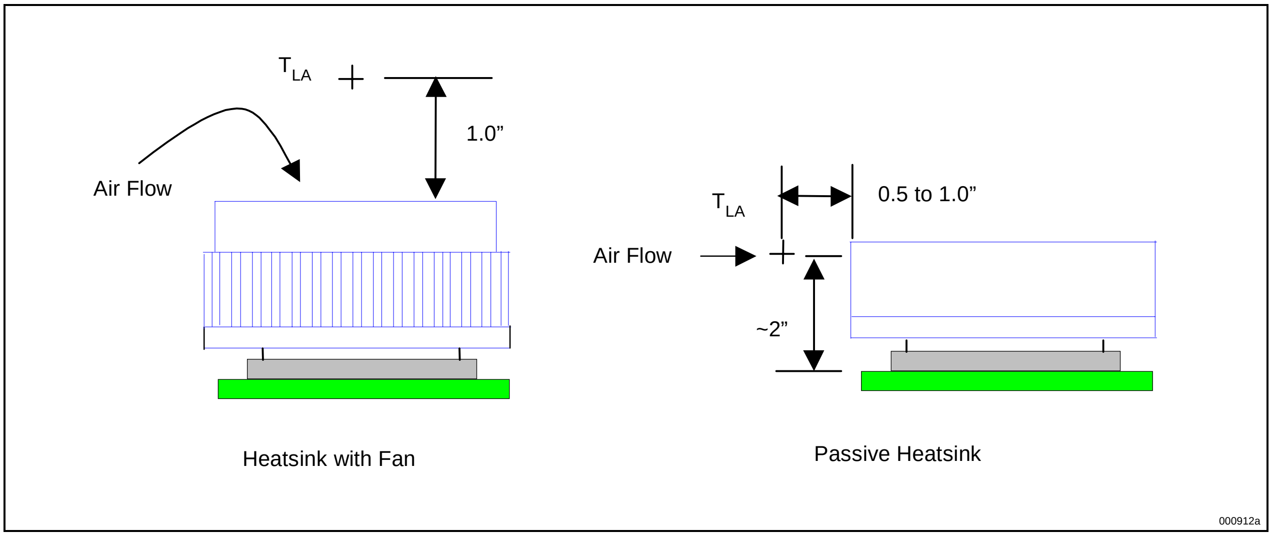


Figure 7. Guideline Locations for Measuring Local Ambient Temperature

7.1.4 Measurements for Processor Thermal Specifications

To appropriately determine the thermal properties of the system, measurements must be made. Guidelines have been established for proper techniques for measuring processor temperatures. The following sections describe these guidelines for measurement.

7.1.4.1 Processor Case Temperature Measurements

To ensure functionality and reliability, the Pentium® 4 processor is specified for proper operation when T_{CASE} is maintained at or below the value listed in the *Pentium 4 processor in the 423-pin Package Datasheet*. The measurement location for T_{CASE} is the geometric center of the IHS. Figure 8 shows the location for T_{CASE} measurement.

Special care is required when measuring the T_{CASE} to ensure an accurate temperature measurement. Thermocouples are often used to measure T_{CASE}. Before any temperature measurements are made, the thermocouples must be calibrated. When measuring the temperature of a surface, which is at a different temperature from the surrounding local ambient air, errors could be introduced in the measurements. The measurement errors could be due to having a poor thermal contact between the thermocouple junction and the surface of the integrated heat spreader, heat loss by radiation, convection, by conduction through thermocouple leads, or by contact between the thermocouple cement and the heat sink base. To minimize these measurement errors, the following approach is recommended:

- Prepare 36 gauge or finer diameter K, T, or J type insulated thermocouples.
- Ensure that the thermocouple has been properly calibrated.
- The thermocouple should be attached at a 90° angle to the integrated heat spreader and the heat sink covers the location specified for T_{case} measurement.
- Drill a hole 0.150 inches (3.8mm) maximum diameter through the heat sink base. This hole must be positioned on the heat sink base so that it matches with the center of the IHS when assembled. This hole will reduce the heat sink performance by approximately 0.02 °C/W.
- Create a small depression, approximately 1/16 inch (1.5mm) in diameter by 1/64 inch (.4mm) deep at the center of the IHS (see Figure 8). This will facilitate the attach procedure by keeping the thermocouple centered and hosting the adhesive.

- Route the thermocouple wires through the hole in the heat sink base and attach it to the processor IHS. The use of more viscous adhesives and minimizing the use of drying accelerators will prevent problems with the adhesive spreading.
- A small fixture may be required to hold the thermocouple and apply a steady force during the curing process to ensure the thermocouple is making contact with the IHS. A Digital Multi-Meter can be used to check continuity between the IHS and the connector as the adhesive cures.
- Make sure there is no contact between the thermocouple adhesive and heat sink base. Contact will affect the thermocouple reading.
- Verify the cured adhesive bead is smaller than 0.15 inches (3.8mm) in diameter and height so as to fit in the hole drilled in the heat sink base. Trim as necessary.
- Place the TIM on the heat sink base. If it is a semi-liquid type apply it on the IHS around the thermocouple. The clamping force will spread the TIM. If the TIM is a solid type, punch a 0.15inch (3.8mm) diameter hole in the center of the TIM pad and cut a line from a side to the hole. This will allow the installation of the TIM to the IHS with the thermocouple already attached to the IHS

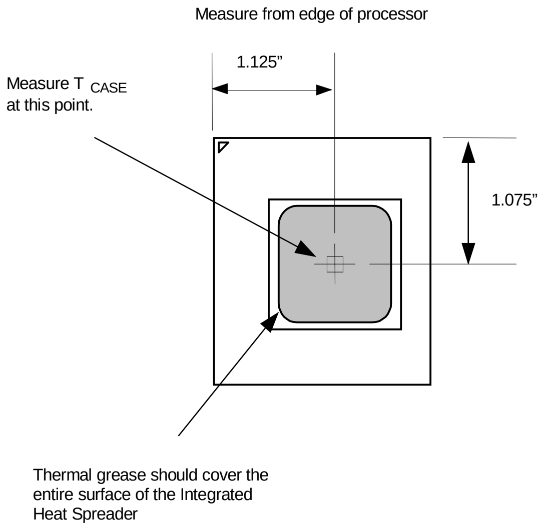


Figure 8. Processor IHS Temperature Measurement Location

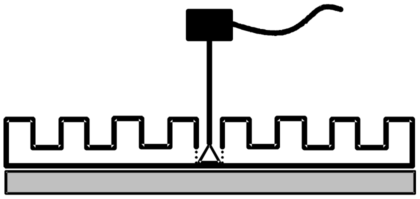


Figure 9. Technique for Measuring with 90° Angle Attachment

7.2 Thermal Test Vehicle to Processor Thermal Performance Correction Factor

Intel releases Thermal Test Vehicles (TTV) for use by system and heat sink solution thermal designers prior to processor availability. The Thermal Test Vehicles approximate the thermal behavior of the processor; however, there is typically a difference in power density and power uniformity. Any thermal solution performance measured on Thermal Test Vehicles requires the application of a TTV-to-CPU correction factor in order to predict that thermal solution performance on a processor. For the Pentium® 4 processor, a TTV-to-CPU correction factor is not necessary.

8 THERMAL MANAGEMENT LOGIC AND THERMAL MONITOR FEATURE

8.1 Processor Power Dissipation

An increase in processor operating frequency not only increases system performance, but also increases the processor power dissipation. The relationship between frequency and power is generalized in the following equation: $P=CV^2F$ (where P = power, C = capacitance, V = voltage, F = frequency). From this equation it is evident that Power increases linearly with frequency and with the square of voltage. In the absence of power saving technologies, ever increasing frequencies will result in processors with power dissipations in the hundreds of Watts. Fortunately, there are numerous ways to reduce the power consumption of a processor. Decreasing the voltage and transistor size are two examples, a third is clock modulation, which is used extensively in laptop designs.

Clock modulation is defined as periodically removing the clock signal from the processor core, which effectively reduces its power consumption to a few Watts. A zero watt power dissipation level is not achievable due to transistor leakage current and the need to keep a few areas of the processor active (cache coherency circuitry, phase lock loops, interrupt recognition, etc.). Therefore, by cycling the clocks on and off at a 50% duty cycle, the average power dissipation can drop by up to 50%. Note that the processor performance will also drop by about 50% during this period, since program execution halts while the clocks are removed. Varying the duty cycle will have a corresponding influence on power dissipation and processor performance.

Laptop systems use clock modulation to control system and processor temperatures. By using various external measurement devices, laptops monitor the processor case temperature and turn on fans or initiate clock modulation to reduce processor power dissipation and ensure that all elements of the system operate within their temperature specifications. Unfortunately, using thermocouples on the processor packages have some inherent disadvantages when used to control a thermal management mechanism. Thermal conductivity (Θ_{JC}) through the processor package creates a gradient between the processor case and silicon temperatures. This delta may be large with the silicon temperature always being higher than the case temperature. Since thermocouples measure case temperature, not silicon temperature, a significant guard band may be necessary to ensure the processor silicon does not exceed its maximum specification. Or, more clearly, clock modulation may have to be turned on when the case temperature is significantly below maximum specification to ensure the processor does not overheat. This large guard band will have a substantial, and unacceptable, impact on system performance.

Thermal ramp rates, or change in die temperature over a specified time period ($\Delta T/\Delta t$), may be extremely high in high power processors where ramp rates in excess of 50°C/sec are anticipated to be normal. With this type of thermal characteristic, it would not be possible to control fans or other cooling devices based on processor temperature. By the time the fans have spun up to speed, the processor may be well beyond a safe operating temperature, which would render any increase in cooling capability useless. Just as large guardbands would be necessary due to package thermal gradients, equally large guardbands would be necessary if temperature controlled fans were implemented.

Clearly, a new thermal management approach is needed to support the continued increases in processor frequency and performance.

A new on-die thermal management feature on the Pentium® 4 processor called Thermal Monitor, resolves these issues so that thermocouples are no longer needed. By using a highly accurate on-die temperature sensing circuit and a fast acting temperature control circuit (~50ns) the processor can rapidly initiate thermal management control. As a result, large guard bands are unnecessary and the system performance impact is minimized if not eliminated.

8.2 Thermal Monitor Implementation

On the Pentium 4 processor, a new thermal management feature called Thermal Monitor is integrated into the processor silicon. Thermal Monitor includes a highly accurate on-die temperature sensing circuit, a signal which indicates the processor is too hot (PROCHOT#), registers to determine the processor thermal status and a thermal control circuit which can reduce the processor temperature by modulating the processor clocks. The processor temperature is determined through an analog thermal sensor circuit comprised of a diode; a factory calibrated reference current source, and a current comparator (see Figure 10). A voltage applied across the diode will induce a current flow that varies with temperature. By comparing this current with the reference current, the processor temperature can be determined. The reference current source corresponds to the diode current when at the maximum permissible processor operating temperature. Each processor is individually calibrated during manufacturing to eliminate any potential manufacturing variations. Once configured, the processor temperature at which the PROCHOT# signal is asserted (trip point) is not re-configurable.

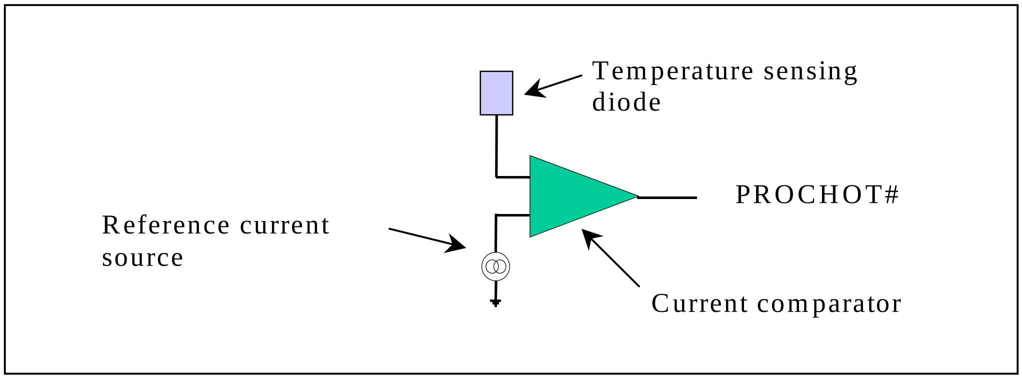


Figure 10. Thermal Sense Circuit

The PROCHOT# signal is available both internally to the processor as well as externally. External indication of the processor temperature status is provided through the bus signal PROCHOT#. When the processor temperature is equal to or above the trip point, PROCHOT# is asserted. When the processor temperature is below the trip point, PROCHOT# is deasserted. Assertion of the PROCHOT# signal is independent of any register settings within the processor and will be asserted any time the processor die temperature is equal to or exceeds the trip point. The point where the thermal control circuit goes active will be set to approximately the same temperature (case temperature) at which the processor is tested. This value is specified in the processor datasheet.

The Thermal Monitor's thermal control circuit, when active, lowers the processor temperature by modulating the internal processor clocks. The thermal control circuit will turn the processor clocks off and then back on with a 50% duty cycle of approximately 4µs in length for an 1.5 GHz processor (~2 µs on, ~2µs off). Refer to Figure 11 for an illustration. Cycle times are processor speed dependent and will decrease linearly as processor core frequencies increase.

An ACPI register, performance counter register, and model specific register (MSR) support are available to monitor and control the Thermal Monitor feature. Details regarding the use of these registers are described in the IA32 Intel Architecture Software Developer Manuals.

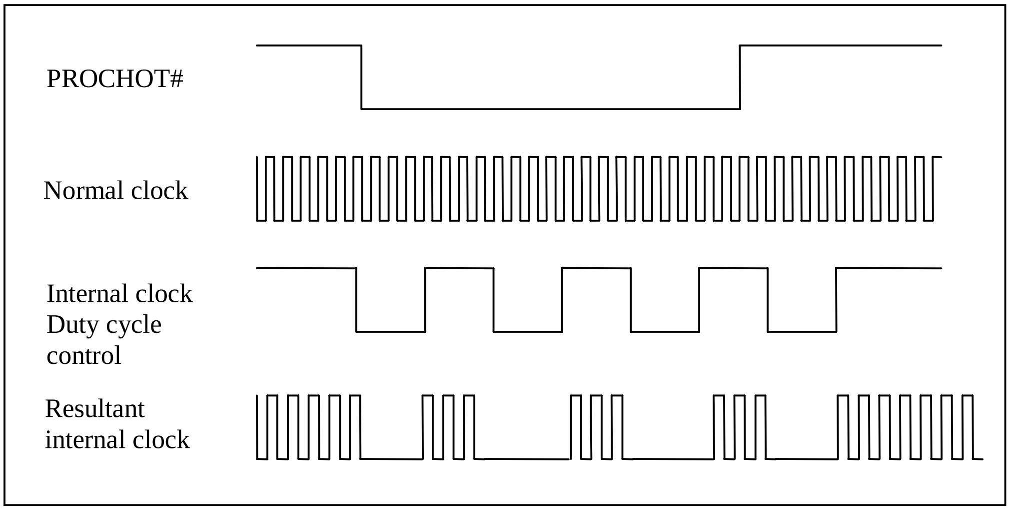


Figure 11. Internal Clock Modulation

8.3 Operation and Configuration

The Thermal Monitor Feature is always enabled. But, to maintain compatibility with previous generations of processors having no integrated thermal logic, the clock modulation portion of Thermal Monitor is disabled by default. During the boot process, the BIOS must enable the thermal control circuit; or a software driver may do this after the operating system has booted. Refer to the IA32 Intel Architecture Software Developer Manuals for programming details.

The thermal control circuit feature can be configured and monitored in a number of ways. OEMs are expected to enable the thermal control circuit while using various registers and outputs to monitor the processor thermal status. The thermal control circuit is enabled by BIOS setting a bit in an MSR (model specific register). Enabling the thermal control circuit allows the processor to maintain a safe operating temperature without the need for special software drivers or interrupt handling routines. When the thermal control circuit has been enabled, it will be active about 50 ns after detecting a high temperature (i.e. ~50 ns after PROCHOT# is asserted). The thermal control circuit and PROCHOT# go inactive once the temperature has been brought back down below the thermal trip point, although a small hysteresis (~1 °C) has been included to prevent multiple PROCHOT# transitions around the trip point. External hardware can monitor PROCHOT# and generate an interrupt whenever there is a transition from active-to-inactive or inactive-to-active. PROCHOT# can also be configured to generate an internal interrupt which would initiate an OEM supplied interrupt service routine. Regardless of the configuration selected, PROCHOT# will always indicate the thermal status of the processor.

For testing purposes, the thermal control circuit may also be activated by setting bits in the ACPI-compliant MSRs. The MSRs may be set based on a particular system event (such as an interrupt generated after a system event), or may be set at any time through OS or custom driver control thus forcing the thermal control circuit on. Activating the thermal control circuit may be useful for cooling solution investigations or for performance implication studies. When using the MSRs to activate the Thermal Monitor feature, the duty cycle is configurable in steps of 12.5% from 12.5 to 87.5%. For any duty cycle, the maximum time the clocks will be disabled is ~2 µs. To achieve different duty cycles, the interval between stopping the clocks is automatically adjusted to achieve the desired ratio. For example, if a duty cycle of ¼ (25%) were to be selected, the clock off time would be 2 µs, while the clock on time would be reduced to approximately 0.66 µs [on time (0.66 µs) ÷ total cycle time (2 + 0.66) µs = ¼ duty cycle]. Similarly, for a duty cycle of 7/8 (87.5%), the clock on time would be extended to 14 µs [14 ÷ (14 + 2.) = 7/8 duty cycle].

In a high temperature situation, if the automatic thermal control circuit and ACPI-compliant MSRs are used simultaneously, the 50% duty cycle will take precedence.

8.4 System Considerations

The Thermal Monitor feature may be used in a variety of ways, depending upon the system design requirements and capabilities. Intel requires the thermal control circuit to be enabled for all Pentium® 4 processor systems. At a minimum, the thermal control circuit supplies an added level of safety against loss in processor availability due to an over temperature situation.

Each application program, which is comprised of thousands of processor instructions, will have its own unique power profile, although the profile will have some variability due to loop decisions, I/O activity and interrupts. In general, compute intensive applications with a high cache hit rate will dissipate more processor power than applications that are I/O intensive or have low cache hit rates.

In order to gain a more thorough understanding of application power levels, Intel has estimated the power dissipation of a number of popular software applications. The method involved required extraction of actual code sequences from the programs and calculating the power consumed if that program were to be run on a Pentium 4 processor. Code sequences, or traces, were gathered from roughly 200 applications and benchmarks. These included Transaction Processing Performance Council TPC-C, SPEC*, SPECint* SPECfp, SPECweb, Ziff-Davis* 3Dwinbench* and Winstone*, Microsoft* desktop applications, id Software* Quake*, CorelDraw*, Video playback with Intel® MMX™ enhanced technology, several of which were run under multiple operating systems. (Including Microsoft Windows* 98, Microsoft Windows NT* and Linux*) and other compute intensive applications. See Figure 12 for a sample distribution of application power.

Processor power dissipation simulations indicate a maximum application power in the range of 75% of the maximum power for a given frequency. Therefore, a system designed to the thermal design point, which has been set to approximately 75% of the maximum processor power would be unlikely to see the thermal control circuit active and experience the associated performance reduction. Systems designed for lower power dissipation could be subject to activation of the thermal control circuit depending upon ambient air temperature and software application power profile. Figure 13 plots processor performance with the Thermal Control Circuit enabled versus system cooling capability. System designers must evaluate the tradeoffs between cooling costs and risk of processor performance loss to determine the optimum configuration for the end user.

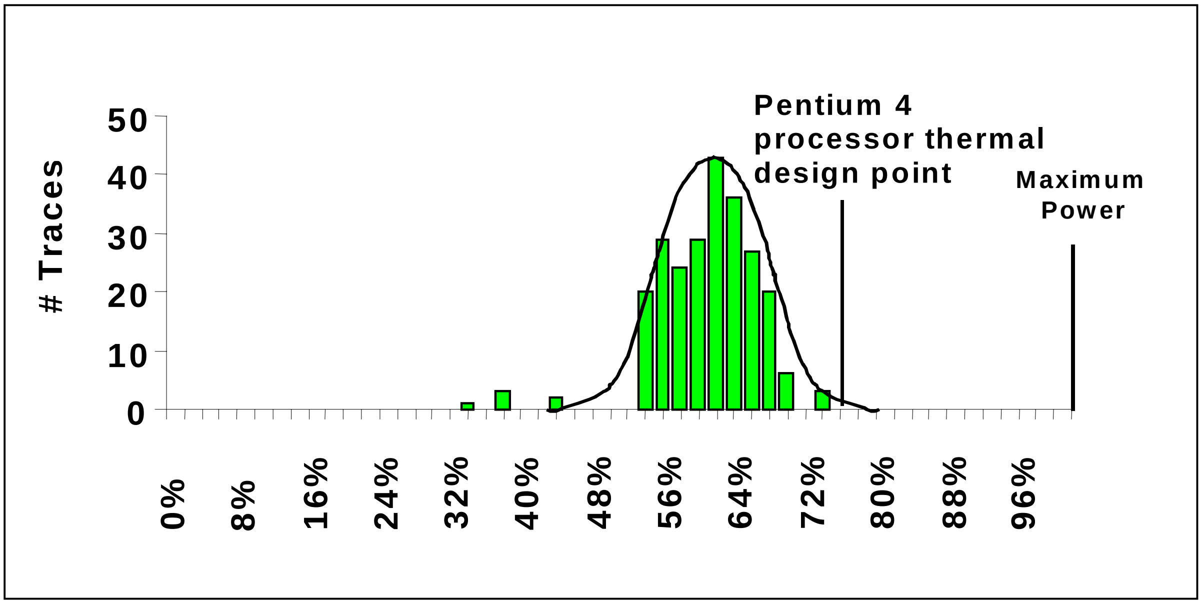


Figure 12. Application Power Dissipation Estimates for the Pentium 4 processor

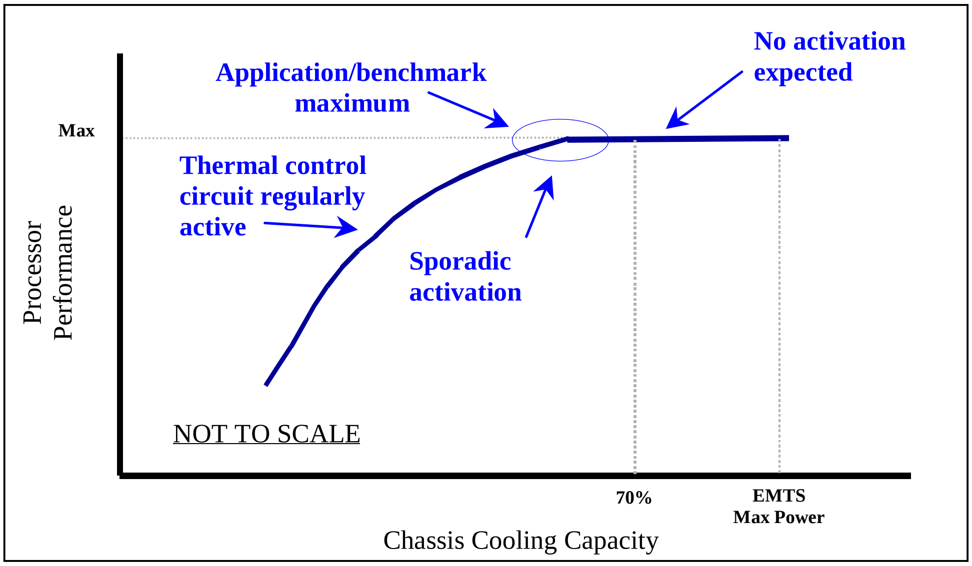


Figure 13. Processor Performance versus System Cooling Capability

8.4.1 Operating System & Application Software Considerations

The Thermal Monitor feature and its thermal control circuit works seamlessly with any ACPI compliant operating system. The Thermal Monitor feature is transparent to application software since the processor bus snooping, ACPI timer and interrupts are active at all times.

8.4.1.1 Operating System Support

Activation of the thermal control circuit during a non-ACPI aware operating system boot process may result in incorrect calibration of operating system software timing loops. The BIOS must disable the thermal control circuit prior to boot and then the operating system or BIOS must enable the thermal control circuit after the operating system boot process completes. Refer to the IA32 Intel Architecture Software Developer Manuals for specific programming details.

Intel is working with the major operating system vendors to ensure support for non-execution based operating system calibration loops and ACPI support for the Thermal Monitor feature. Per Microsoft, Microsoft* Windows* 98ES and Windows 2000 use non-execution based calibration loops and therefore have no issues with the Thermal Monitor feature. When installing Windows NT* 4.0, the user must ensure the APIC-based HAL is used. It is expected that other OS solutions (Linux*, Unix*, etc) will provide updates to ensure compatibility.

8.5 Legacy Thermal Management Capabilities

In addition to Thermal Monitor, the Pentium® 4 processor supports the same thermal management features as available on the Intel Pentium III processor. These features are the on-die thermal diode and THERMTRIP# signal for indicating catastrophic thermal failure.

8.5.1 Thermal Diode

The Pentium 4 processor incorporates an on-die thermal diode, which can be used with an external device (thermal diode sensor) to monitor long-term temperature trends. By averaging this data over long time periods (hours/days vs. min/sec), it may be possible to derive a trend of the processor temperature. Analysis of this information could be useful in detecting changes in the system environment that may require attention. Design characteristics and usage models of the thermal diode sensors are described in datasheets available from the thermal diode sensor manufacturers.

The processor thermal diode should not be relied upon to turn on fans, warn of processor cooling system failure or predict the onset of thermal control circuit. As mentioned earlier, the processor's high thermal ramp rates make this unfeasible. An illustration of this is as follows. Many thermal diode sensors report temperatures a maximum of 8 times per second. Within the 1/8th (0.125 sec) second time period, the thermal diode temperature is averaged over 1/16th of a second. In a worst case scenario where the silicon temperature ramps at 30°C/sec, or ~3.75°C/0.125 sec, the processor will be ~3°C above the temperature reported by the thermal diode sensor. (Change in diode temperature averaged over 1/16th seconds = ~1°C, temperature reported 1/16th second later at 1/8th second when the actual processor temperature would be 3.75°C higher, see Figure 14)

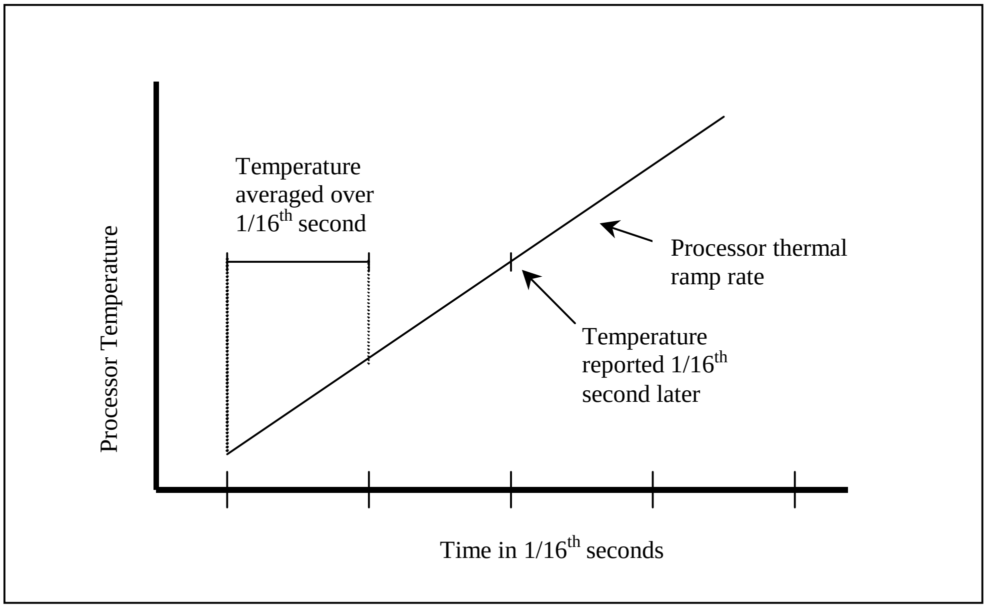


Figure 14. Thermal Diode Sensor Time Delay

8.5.2 THERMTRIP#

In the event of a catastrophic cooling failure, the processor will automatically shut down when the silicon temperature has reached approximately ~135 °C. At this point the system bus signal THERMTRIP# will go active and stay active until the processor has cooled down and RESET# has been initiated. THERMTRIP# activation is independent of processor activity and does not generate any bus cycles.

8.5.3 Thermal Measurement Correlation

There are two independent thermal diodes in the Pentium® 4 processor; one for the thermal diode and one for the Thermal Monitor, which is also used for THERMTRIP#. The Thermal Monitor's temperature sensor and the thermal diode are independent and isolated devices with no direct correlation to one another. Circuit constraints and performance requirements prevent the Thermal Monitor sensor, and thermal diode from being located at the same location on the silicon. As a result, it will not be possible to predict the activation of the thermal control circuit by monitoring the thermal diode

If desired, the system may be designed to cool the maximum processor power levels. In this situation, it may be useful to use the PROCHOT# signal as an indication of cooling system failure. Messages could be sent to the system administrator to warn of the cooling failure, while thermal control circuit would allow the system to continue functioning or allow a graceful system shutdown. If no thermal management action is taken, the silicon temperature may exceed ~135°C causing THERMTRIP# to go active and shut down the processor. Regardless of the system design requirements or cooling solution ability, the Thermal Monitor feature must still be enabled to guarantee proper processor operation.

9 CONCLUSION

As the complexity of today's microprocessors continues to increase, so do the power dissipation requirements. Care must be taken to ensure that the additional power is properly dissipated. Heat can be dissipated using passive heat sinks, fans and/or active cooling devices. Incorporating ducted airflow solutions into the system thermal design can yield additional margin.

The size and type of the heat sink, as well as the output of the fan can be varied to balance size, cost, and space constraints with acoustic noise. This document has presented the conditions and requirements for designing a heat sink solution for a Pentium® 4 processor-based system. Properly designed solutions provide adequate cooling to maintain the Pentium 4 processor within its thermal specification. This is accomplished by providing a low local ambient temperature and creating a minimal thermal resistance to that local ambient temperature. Fan heat sinks or ducting can be used to cool the processor if proper package temperatures cannot be maintained otherwise. By maintaining the processor's case temperature at the values specified in the processor Datasheet, a system designer can be confident of proper functionality and reliability of these processors.

The Pentium 4 processor has thermal management logic integrated into the processor silicon. This circuit must be configured to automatically control the processor temperature through the use of the Thermal Monitor feature. At a factory-calibrated temperature, the processor will periodically stop the internal clocks in order to reduce power consumption and cool down the processor. Various registers and bus signals are available to monitor and control the processor thermal status.

A chassis cooling solution designed to the TDP as specified in the Datasheet will adequately cool the processor to a level where activation of the Thermal Monitor feature is either very rare or non-existent. Various levels of performance versus cooling capacity are available and must be understood before designing a chassis. Automatic thermal management must be used as part of the total system thermal solution.