



# Intel<sup>®</sup> Pentium<sup>®</sup> 4 Processor in the 478-Pin Package Thermal Design Guidelines

Design Guide

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## Revision History

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Rev. No.	Description	Date
-001	Initial Release.	August 2001
-002	<ul style="list-style-type: none"><li>• Update for the support of the Intel® Pentium® 4 processor with 512 KB L2 cache on .13 micron process</li><li>• Update References</li><li>• Add heatsink attach guidelines</li><li>• Add a note on active heatsink validation (<math>T_A</math> measurement section)</li><li>• Update TTV information and utilization</li><li>• Update reference heatsink performance target</li><li>• Update reference mechanical component information</li></ul>	January 2002
-003	<ul style="list-style-type: none"><li>• Update references</li></ul>	May 2002

# 1 *Introduction*

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In this document, when a reference is made to the processor and/or the Intel® Pentium® 4 processor in the 478-pin package, it is intended that this includes the Intel® Pentium® 4 processor in the 478-pin package and the Intel® Pentium® 4 processor with 512 KB L2 cache on .13 micron process, unless it is otherwise specified. When a reference is intended to refer to a specific processor, the specific processors will be listed separately.

This design guide supports the following processors:

- Intel® Pentium® 4 processor in the 478-pin package
- Intel® Pentium® 4 processor with 512KB L2 cache on .13 micron process

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

In a system environment, the processor temperature is a function of both system and component thermal characteristics. The system level thermal constraints consist of the local ambient air temperature and airflow over the processor as well as the physical constraints at and above the processor. The processor 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 processor performance levels (higher operating speeds, GHz) and packaging density (more transistors). As operating frequencies increase and packaging size decreases, the power density increases while the thermal cooling solution space and airflow typically become more constrained or remain the same within the system. The result is an increased importance on system design to ensure that thermal design requirements are met for each component, including the processor, in the system.

The thermal power of the Intel Pentium 4 processor in the 478-pin package and the Intel Pentium 4 processor with 512KB L2 cache on .13 micron process generations is higher, as well as more dense, 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 requirements imposed on single processor systems.

Chapter 2 of this document discusses thermal solution design guidelines for the Intel Pentium 4 processor in the 478-pin package, in the context of personal computer application. This chapter also includes thermal metrology recommendations to validate a processor cooling solution. It addresses also the benefits of the processor integrated thermal management logic on thermal design. Chapter 3 details the critical to function dimensions of the Intel reference cooling solution for the processor.



The physical dimensions and thermal specifications of the processor that may be used in this document are for illustration only. Refer to the corresponding processor datasheet for the product dimensions, thermal power dissipation and maximum case temperature. In case of conflict, the data in the datasheet takes precedence over any data in this document.





## 1.1 References

Material and concepts available in the following documents may be beneficial when reading this document.

Document	Order Number
Intel® Pentium® 4 Processor in the 478-pin Package Datasheet	249887
Intel® Pentium® 4 Processor with 512KB L2 Cache on.13 Micron Process Datasheet	298643
Intel® Pentium® 4 Processor in the 478-pin Package and Intel® 850 Chipset Platform Design Guide	249888
Intel® Pentium® 4 Processor in the 478-pin Package and Intel® 845 Chipset Platform Design Guide	298354
Intel® Pentium® 4 Processor 478-Pin Socket (mPGA478B) Design Guidelines	249890
Mechanical Enabling for the Intel® Pentium® 4 Processor in the 478-Pin Package	290728
IA-32 Intel Architecture Software Developer's Manual: Volume III System Programming Guide	245472

To obtain these documents visit the Intel web site at <http://developer.intel.com/>.

## 1.2 Definition of Terms

Term	Description
$T_A$	The measured ambient temperature locally surrounding the processor. The ambient temperature should be measured just “upstream” of a passive heatsink, or at the fan inlet for an active heatsink (see Figure 3).
$T_E$	The measured ambient temperature outside of the system.
$T_C$	The measured case temperature of the Intel Pentium 4 processor in the 478-pin package, as defined in Figure 1 and as specified in the processor datasheet.
TIM	Thermal Interface Material – The thermally conductive compound between the heatsink and the processor case. This material fills the air gaps and voids, and enhances the spreading of the heat from the processor case to the heatsink.
$\theta_{CA}$	The thermal resistance between the processor case and the ambient air. This is defined and controlled by the system thermal solution. $\theta_{CA}$ includes both $\theta_{CS}$ and $\theta_{SA}$ .
$\theta_{CS}$	The case to sink thermal resistance, mainly due to the thermal interface material.
$\theta_{SA}$	The thermal resistance between the heatsink base and the ambient air. This is defined and controlled by the system thermal solution.
478-Pin Socket	The surface mount Zero Insertion Force (ZIF) socket designed to accept the Intel Pentium 4 processor in the 478-pin package.
ACPI	Advanced Configuration and Power Interface.
Bypass	Bypass is the area between a passive heatsink 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.



Term	Description
Thermal Monitor	The Intel Pentium 4 processor in the 478-pin package implements thermal management features consisting of: an on-die thermal diode, reference current source, comparator, external bus signal, thermal control circuit and processor registers to assist with managing thermal control of the processor.
Thermal Control Circuit (TCC)	The portion of Thermal Monitor, which modulates the clocks during an over-temperature event.
Thermal Design Power (TDP)	A power dissipation target based on worst-case applications. Thermal solutions should be designed to dissipate the thermal design power.

## 2 Thermal Mechanical Information

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### 2.1 Mechanical Requirements

#### 2.1.1 Processor Package

The Intel® Pentium® 4 processor in the 478-pin package is packaged in a flip-chip pin grid array 2 (FC-PGA2) package technology. Please refer to the processor datasheet for detailed mechanical specifications of the 478-pin package.

The package includes an integrated heat spreader (IHS). The IHS spreads the non-uniform heat from the die to the top of the IHS, out of which the heat flux is more uniform and on a larger surface area. This allows more efficient heat transfer out of the package to an attached cooling device. The IHS is designed to be the interface for mounting a heatsink. Details can be found in the processor datasheet.

The processor connects to the motherboard through a ZIF surface mount socket. A description of the socket can be found in the *Intel® Pentium® 4 Processor, 478-Pin Socket (mPGA478B) Design Guidelines*.

The processor package has mechanical load limits that are specified in the datasheet. These load limits should not be exceeded during heatsink installation, removal, mechanical stress testing, or standard shipping conditions. For example, when a compressive static load is necessary to ensure thermal performance of the thermal interface material between the heatsink base and the IHS, this compressive static load should not exceed the compressive static load specification given in the processor datasheet.

The heatsink mass can also add additional dynamic compressive load to the package during a mechanical shock event. Amplification factors due to the impact force during shock have to be taken into account in dynamic load calculations. The total combination of dynamic and static compressive load should not then exceed the processor datasheet compressive dynamic load specification during a vertical shock. For example, with a 1 lbm heatsink, an acceleration of 50 g during a 11ms shock results approximately in a 100 lbf dynamic load on the processor package. If a 100 lbf static load is also applied on the heatsink for thermal performance of the thermal interface material and/or for mechanical reasons, the processor package sees 200 lbf. The calculation for the thermal solution of interest should be compared to the processor datasheet specification.

It is not recommended to use any portion of the substrate as a mechanical reference or load-bearing surface in either static or dynamic compressive load conditions.



## 2.1.2 Heatsink Attach

There are no features on the mPGA478 socket to directly attach a heatsink: a mechanism must be designed to support the heatsink. In addition to holding the heatsink into place on top of the IHS, this mechanism plays a significant role in the robustness of the system in which it is implemented, in particular:

- Ensuring thermal performance of the thermal interface material used between the IHS and the heatsink. Some of these materials are very sensitive to pressure applied to them, the higher the pressure, the better the performance.
- Ensuring system electrical, thermal and structural integrity under shock and vibration events. The mechanical requirements of the attach mechanism depend on the weight of the heatsink and the level of shock and vibration that the system has to support. The overall structural design of the motherboard and the system has to be considered as well when designing the heatsink attach mechanism, in particular their impact on motherboard stiffening needed to protect mPGA478 socket solder joint, and prevent package pull-out from the socket.

A popular solution for heatsink attach mechanism is to use a retention mechanism and attach clips. In that case, the clips should be designed to the general guidelines given above, and more specifically:

- To hold the heatsink in place under shock and vibration events and apply force to the heatsink base to maintain desired pressure on the thermal interface material. The load applied by the clip also plays a role in ensuring that the package does not disengage from the socket during mechanical shock testing. Note that the load applied by the clips must comply with the package specifications described section 2.1.1 along with the dynamic load added by the shock and vibration requirements.
- To engage easily with the retention mechanism tabs, if possible without the use of special tools. This should also take into account that, in general, heatsink and clip are installed once the motherboard has been installed into the chassis.
- To minimize contact with the motherboard surface during clip attach to the retention mechanism tab features; the clip should not scratch the motherboard.

The Intel Reference design for the Intel® Pentium® 4 processor in the 478-pin package is using such a retention mechanism and clip assembly. Refer to section 3.3 and the document *Mechanical Enabling for the Intel® Pentium® 4 processor in the 478-Pin Package* for further information regarding the Intel Reference mechanical solution.

## 2.2 Thermal Specifications

### 2.2.1 Processor Case Temperature and Power Dissipation

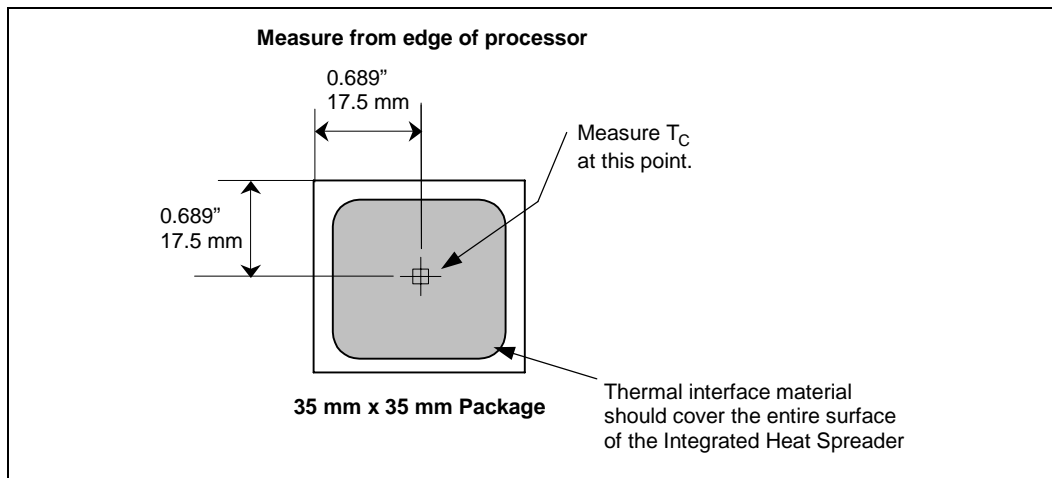
Refer to the processor datasheet for processor thermal information.

Thermal information for the processor is given in terms of maximum case temperature specification and thermal design power. These values may depend on the processor frequencies and also include manufacturing variations. Designing to these values allows optimizing thermal design for processor performance (refer to section 2.4).

Processor power is dissipated through the IHS. There is no additional component, i.e., BSRAMs, which generates heat on this package.

The case temperature is defined as the temperature measured at the center of the top surface of the IHS. For illustration, the measurement location for a 35 mm x 35 mm FC-PGA2 package is shown in Figure 1. Techniques for measuring the case temperature are detailed in Section 2.3.3.

**Figure 1. Processor IHS Temperature Measurement Location**



### 2.2.2 Designing a Cooling Solution for the Intel® Pentium® 4 Processor in the 478-Pin Package

#### 2.2.2.1 Heatsink Solutions

##### 2.2.2.1.1 Heatsink Design Considerations

Considering the power dissipation levels and typical local ambient temperature near the processor around 45°C in a majority of chassis, the processor temperature cannot be maintained at or below the specified guidelines without additional thermal enhancement to dissipate the heat generated by the processor. For the Intel Pentium 4 processor in the 478-pin package, a typical aluminum



extruded heatsink may not be sufficient to cool the entire range of thermal design power. It is expected that more advanced cooling techniques will be necessary.

In designing a cooling solution, 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.

To remove the heat from the processor, three basic parameters have to be considered:

- **The area of the surface on which the heat exchange takes place.** Without any enhancements, this is the surface of the IHS. One method used to improve thermal performance is to increase the surface area of the IHS by attaching a heatsink to it. Heatsinks extend the heat exchange surface through the use of fins that can be of various shapes, and are attached to a heatsink base in contact with the IHS.
- **The conduction path from the heat source to the heatsink fins.** Providing a direct conduction path from the heat source to the heatsink fins and selecting materials with higher thermal conductivity typically improve heatsink performance. The length, thickness, and conductivity of the conduction path from the heat source to the fins will directly impact the thermal performance of the heatsink. In particular, the quality of the contact between the package IHS and the heatsink base has higher impact on the overall cooling solution performance as processor cooling requirements become more strict. Thermal interface material (TIM) can be used to fill in the gap between the IHS and the bottom surface of the heatsink, and thereby improve the overall performance of the stack-up (IHS-TIM-Heatsink). Although, with extremely poor heatsink interface flatness or roughness, TIM may not adequately fill the gap. The TIM thermal performance depends on its thermal conductivity as well as the pressure load applied to it. Refer to Appendix A for further information regarding managing the bond line between the IHS and the heatsink base.
- **The heat transfer conditions on the surface on which heat transfer takes place.** Convective heat transfer occurs between the airflow and the surface exposed to the flow. It is characterized by the local ambient temperature of the air and the local air velocity over the surface. The higher the air velocity and turbulence over the surface, and the cooler the air, the more efficient is the resulting cooling. In the case of a heatsink, the surface exposed to the flow includes in particular the fin faces and the heatsink base.

**Active heatsinks** typically incorporate a fan that helps manage the airflow through the heatsink.

**Passive heatsink** solutions require an in-depth knowledge of the airflow in the chassis. Typically, passive heatsinks may see lower air speed, and are therefore larger (and heavier) than active heatsinks due to the increase in fin surface required to meet a required performance. As the heatsink fin density (the number of fins in a given cross-section) increases, the resistance to the airflow increases: it is more likely that the air travels around the heatsink instead of through it, unless air bypass is carefully managed. Using air-ducting techniques to manage bypass can be an effective method for controlling airflow through the heatsink.

### 2.2.2.1.2 Thermal Interface Material

Thermal interface material application between the processor IHS and the heatsink base is generally required to improve thermal conduction from the IHS to the heatsink. Many thermal interface materials can be pre-applied to the heatsink base prior to shipment from the heatsink supplier and allow direct heatsink attach, without the need for a separate thermal interface material dispense or attach process in the final assembly factory.

All thermal interface materials should be sized and positioned on the heatsink base in a way that ensures the entire processor IHS area is covered. It is important to compensate for heatsink-to-processor attach positional alignment when selecting the proper thermal interface material size.

When pre-applied material is used, it is recommended to have a protective application tape over it. This tape must be removed prior to heatsink installation.

### 2.2.2.1.3 Summary

In summary, considerations in heatsink design include:

- The local ambient temperature at the heatsink, the power being dissipated by the processor, and the corresponding maximum  $T_c$  at the processor frequency considered. These parameters are usually combined in a single lump cooling performance parameter,  $\Theta_{CA}$  (case to air thermal resistance). More information on the definition and the use of  $\Theta_{CA}$  is given Section 2.2.2.2 and Section 2.2.2.3.
- Heatsink interface (to IHS) surface characteristics, including flatness and roughness.
- The performance of the thermal interface material used between the heatsink and the IHS.
- Surface area of the heatsink.
- Heatsink material and technology.
- Volume of airflow over the heatsink surface area.
- Development of airflow entering and within the heatsink area.
- Physical volumetric constraints placed by the system.

## 2.2.2.2 Characterizing Cooling Performance Requirements

The notion of “thermal resistance” is convenient to characterize the performance needed for the cooling solution and to compare cooling solutions in identical situations. Be aware, however, of its limitation when it comes to a real design. Heat transfer is a three-dimensional phenomenon that can rarely be accurately and easily modeled by lump values.

The thermal resistance value from case-to-local ambient ( $\Theta_{CA}$ ) is used as a measure of the thermal performance of the overall cooling solution that is attached to the processor package. It is defined by the following equation, and measured in units of °C/W:



$$\Theta_{CA} = (T_C - T_A) / P_D \text{ (Equation 1)}$$

Where:

- $\Theta_{CA}$  = Thermal resistance from case-to-local ambient (°C/W)
- $T_C$  = Processor case temperature (°C)
- $T_A$  = Local ambient temperature in chassis around processor (°C)
- $P_D$  = Processor power dissipation (W) (assume all power goes through the IHS)

The thermal resistance of the processor case-to-local ambient,  $\Theta_{CA}$ , is comprised of  $\Theta_{CS}$ , the thermal interface material thermal resistance, and of  $\Theta_{SA}$ , the sink-to-local ambient thermal resistance:

$$\Theta_{CA} = \Theta_{CS} + \Theta_{SA} \text{ (Equation 2)}$$

Where:

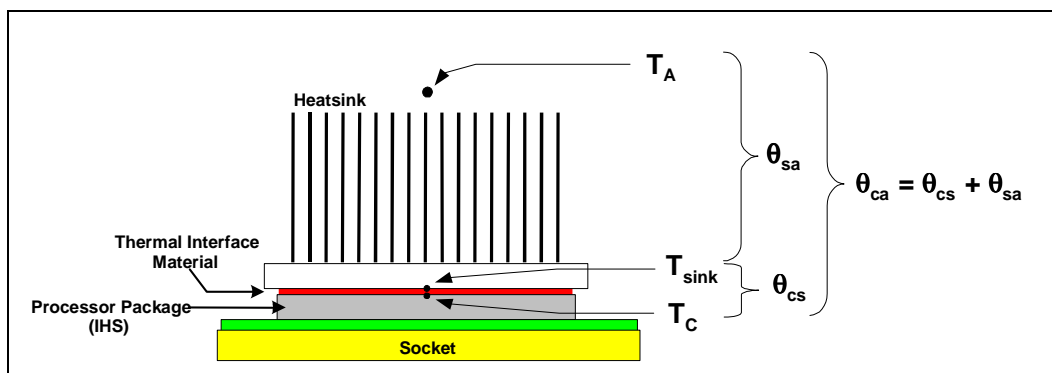
- $\Theta_{CS}$  = Thermal resistance of the thermal interface material (°C/W)
- $\Theta_{SA}$  = Thermal resistance from heatsink-to-local ambient (°C/W)

$\Theta_{CS}$  is strongly dependent on the thermal conductivity and thickness of the TIM between the heatsink and IHS.

$\Theta_{SA}$  is a measure of the thermal resistance from the bottom of the heatsink to the local ambient air.  $\Theta_{SA}$  is dependent on the heatsink's material, thermal conductivity, and geometry. It is also strongly dependent on the air velocity through the fins of the heatsink.

Figure 2 illustrates the combination of the different thermal resistances.

**Figure 2. Processor Thermal Resistance Relationships**





### 2.2.2.3 Example

The cooling performance  $\Theta_{CA}$  is then defined using the notion of thermal resistance described above:

- Define a target case temperature  $T_{C,F}$  and corresponding thermal design power  $TDP_F$  from thermal specifications at a target frequency given in the processor datasheet.
- Define a target local ambient temperature around the processor,  $T_A$ .

Since the processor thermal specifications ( $T_C$  and TDP) can vary with the processor frequency, it may be important to identify the worse case (smallest  $\Theta_{CA}$ ) for a targeted chassis (characterized by  $T_A$ ) to establish a design strategy such that a given heatsink can cover a given range of processor frequencies.

The following provides an illustration of how one might determine the appropriate performance targets. The power and temperature numbers used here are not related to any Intel processor thermal specifications, and are just given to carry out the example.

Assume the datasheet TDP is 55W and the case temperature specification is 70 °C. Assume as well that the system airflow has been designed such that the local ambient temperature is 45°C. Then the following could be calculated using equation 1 from above:

$$\Theta_{CA} = (T_{C,F} - T_A) / TDP_F = (70 - 45) / 55 = 0.45 \text{ } ^\circ\text{C/W}$$

To determine the required heatsink performance, a heatsink solution provider would need to determine  $\Theta_{CS}$  performance for the selected TIM and mechanical load configuration. If the heatsink solution were designed to work with a TIM material performing at  $\Theta_{CS} \leq 0.15 \text{ } ^\circ\text{C/W}$ , solving for equation 2 from above, the performance of the heatsink would be:

$$\Theta_{SA} = \Theta_{CA} - \Theta_{CS} = 0.45 - 0.15 = 0.30 \text{ } ^\circ\text{C/W}$$

### 2.2.2.4 Looking at the Whole Thermal Solution

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 brings in air from the external ambient environment and transports the heat generated by the processor and other system components out of the system. The number, size and relative position of fans and vents have a decisive impact on the chassis thermal performance, and therefore on the ambient temperature around the processor. The size and type (passive or active) of the 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. Additional constraints are board layout, spacing, component placement, and structural considerations that limit the thermal solution size. For more information, refer to the *Performance ATX Desktop System Thermal Design Suggestions* or *Performance microATX Desktop System Thermal Design Suggestions* documents available on the <http://www.formfactors.org/> web site.



In addition to passive heatsinks, fan heatsinks 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.

To develop a reliable, cost-effective thermal solution, thermal characterization and simulation should be carried out at the entire system level, accounting for the thermal requirements of each component. In addition, acoustic noise constraints may limit the size, number, placement, and types of fans that can be used in a particular design.

To ease the burden on cooling solutions the Thermal Monitor feature and associated logic have been integrated into the silicon of the Intel® Pentium® 4 processor in the 478-pin package. By taking advantage of the Thermal Monitor feature, system designers may reduce the cooling system cost while maintaining the processor reliability and performance goals. Implementation options and recommendations are described in Section 2.4.

## 2.3 Thermal Metrology for the Intel® Pentium® 4 Processor in the 478-Pin Package

### 2.3.1 Processor Cooling Solution Performance Assessment

Section 2.3 discusses guidelines for testing thermal solutions, including measuring processor temperatures. In all cases, power dissipation and temperature measurements must be made to validate a cooling solution.

Thermal performance of a processor heatsink in a chassis should be assessed using a thermal test vehicle (TTV) provided by Intel (refer to section 2.3.4). TTV is a well-characterized thermal tool; using real parts introduces other factors that can impact test results. In particular, the power level from real processors varies significantly, even when running the *MaxPower* application provided by Intel, due to variances in the manufacturing process. The TTV provides consistent power and power density for thermal solution characterization and result can be easily translated to real processor performance. Accurate measurement of the power dissipated by a real processor is beyond the scope of this document.

Once the thermal solution and chassis are designed and validated with the TTV, it is recommended to verify functionality of the thermal solution on real processors and on fully integrated systems (see section 2.4). The Intel thermal stressing software *MaxPower* enables steady power dissipation on a processor to assist in this testing.

Contact your Intel field sales representative for the version of *MaxPower* that applies to the processor.

### 2.3.2 Local Ambient Temperature Measurement Guidelines

The local ambient temperature  $T_A$  is the temperature of the ambient air surrounding the processor. For a passive heatsink,  $T_A$  is defined as the heatsink approach air temperature; for an actively cooled heatsink, it is the temperature of inlet air to the active cooling fan.

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

$T_A$  is best measured by averaging temperature measurements at multiple locations in the heatsink inlet airflow. This method helps reduce error and eliminate minor spatial variations in temperature. The following guidelines are meant to enable accurate determination of the localized air temperature around the processor during system thermal testing.

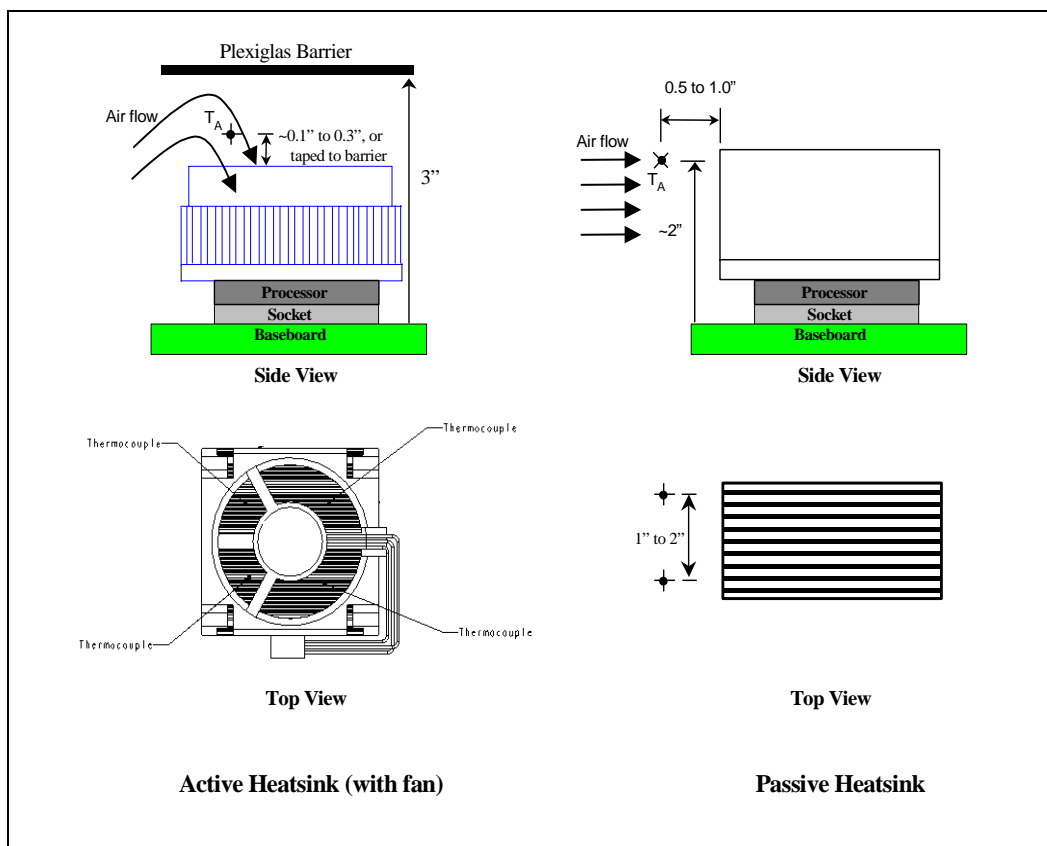
For **active heatsinks**, it is important to avoid taking measurement in the dead flow zone that usually develops above the fan hub. Measurements should be taken at four different locations uniformly placed at the center of the annulus formed by the fan hub and the fan housing to evaluate the uniformity of the air temperature at the fan inlet. The thermocouples should be placed approximately 0.1 to 0.3 inch (2.54 mm to 7.62 mm) above the fan hub vertically, and halfway between the fan hub and the fan housing horizontally as shown in Figure 3. Using an open bench to characterize an active heatsink can be useful, and usually ensures more uniform temperatures at the fan inlet. However, additional tests that include a barrier above the test motherboard surface

can help evaluate the potential impact of the chassis. This barrier is typically clear Plexiglas®, extending at least 4 inches in all directions beyond the edge of the thermal solution. Typical distance from the motherboard to the barrier is 3 inches (76.2 mm) to 3.5 inches (88.9 mm). For even more realistic airflow, the motherboard should be populated with significant elements like memory cards, AGP card, chipset heatsink. If a barrier is used, the thermocouple can be taped directly to the barrier with a clear tape at the horizontal location as previously described, half way between the fan hub and the fan housing. If a variable speed fan is used, it may be useful to add a thermocouple taped to the barrier above the location of the temperature sensor used by the fan to check its speed setting against air temperature. When measuring  $T_A$  directly in a chassis with a live motherboard, add-in cards and the other system components, it is likely that  $T_A$  shows as highly non-uniform across the inlet fan section.

For **passive heatsinks**, thermocouples should be placed approximately 0.5 to 1.0 inches (12.7 mm to 25.4 mm) away from processor and heatsink as shown in Figure 3. The thermocouples should be placed approximately 2 inches (50.8 mm) above the baseboard. This placement guideline is meant to minimize the effect of localized hot spots from baseboard components.

**Note:** Testing active heatsink with a variable speed fan can be done in a thermal chamber to cover the worst-case thermal environment scenarios. Otherwise, when doing a bench top test at room temperature, the fan regulation prevents the heatsink to operate at its maximum capability. To characterize the heatsink capability in the worst-case environment in these conditions, it is then necessary to disable the fan regulation and power the fan directly, after getting direction to do so from the thermal solution provider.

**Figure 3. Guideline Locations for Measuring Local Ambient Temperature (not to scale)**



### 2.3.3 Processor Case Temperature Measurement Guidelines

To ensure functionality and reliability, the Intel® Pentium® 4 processor in the 478-pin package is specified for proper operation when  $T_c$  is maintained at or below the value listed in the processor datasheet. The measurement location for  $T_c$  is the geometric center of the IHS. Figure 1 shows the location for  $T_c$  measurement.

Special care is required when measuring the  $T_c$  to ensure an accurate temperature measurement. Thermocouples are often used to measure  $T_c$ . 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 caused by 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 heatsink base. To minimize these measurement errors, the approach outlined in the next section is recommended.

#### 2.3.3.1 Thermocouple Attachment

This section describes the procedure for attaching a thermocouple to the IHS for the case temperature ( $T_c$ ) measurement.

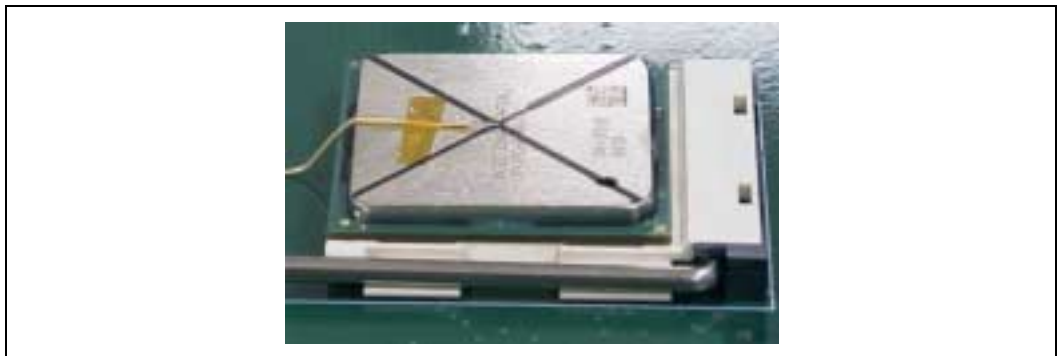
1. Obtain the necessary items needed for the quantity of thermocouple attaches desired:
  - Fine point tweezers
  - Exacto\* knife (#11 blade)
  - Thermocouples (Type K, 36 gauge, 36 inch, Teflon\* insulation). Ensure that the thermocouple has been properly calibrated
  - 3M\* Kapton\* tape (or equivalent) cut into strips (1/8 inch X 1/2 inch)
  - Epoxy (Omegabond\* 101 or equivalent)
  - Curing oven or equivalent.
2. Use a scribe to mark at the center of the package (IHS side) where the bead of the thermocouple will be placed. Determine the center of the package by drawing two diagonal lines across the length of the package. The intersection of the two lines is the package center. (See following figure).

**Figure 4. Desired Thermocouple Location**



3. After the marks are scribed, clean the desired thermocouple attach location with a mild solvent and a lint-free wipe or cloth. Alcohol or acetone should suffice. Cleanliness of the part is critical for a strong epoxy bond after curing.
4. With thermocouple (T/C) in hand, locate the junction and straighten the wire by hand so that the first 4-6 inches are reasonably straight. Use the fine point tweezers to ensure that the bead and the two protruding wires are straight and untwisted. Ensure the second layer of thermocouple insulation, sometimes clear, is not covering the bead.
5. Place a slight downward bend in the protruding wires approximately 1/16 inch from junction using the tweezers. This aids the user in ensuring the thermocouple junction contacts the heat spreader surface.
6. Place the thermocouple on the surface of the part so the bead is contacting the IHS at the desired location. Hold the T/C with one hand and use a pair of tweezers to apply a cut piece of Kapton\* tape across the wire approximately about ¼ inch back from the bead. Apply pressure to the tape to ensure a good bond. Apply additional Kapton\* tape along the length of the wire to ensure a good temporary bond to the part. (See following figure). **Check for electrical continuity between the thermocouple and the IHS using a multimeter.** If there is no electrical continuity between the thermocouple and the IHS, repeat Steps 4-6.

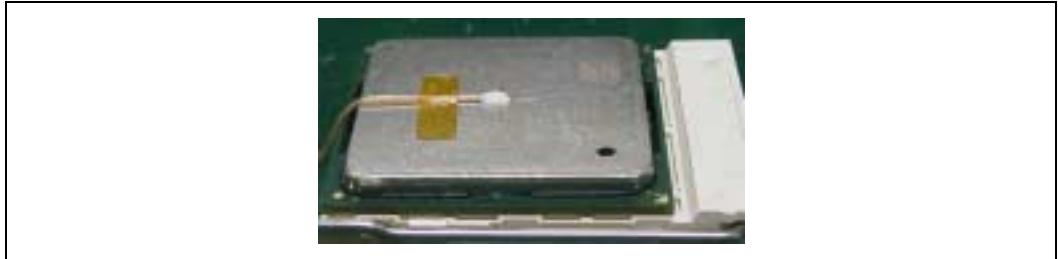
**Figure 5. Location of Kapton\* Tape for Temporary Bond**



7. With the thermocouple temporarily held to the part, apply epoxy to the thermocouple bead for a permanent bond. If applying Omegabond\* 101 epoxy, a small piece of paper works well for mixing. Follow the manufacturer's instructions for mixing.
8. Use the Exacto\* knife or similar to apply the epoxy to the thermocouple bead. Dab glue on the bead and the exposed wires. Use only the appropriate amount of epoxy to cement the thermocouple to the IHS. Excess epoxy will prevent the heatsink from mating flush with the

IHS. The entire bead should be submerged and it is best to have insulated wires protruding from the epoxy. (See following figure).

**Figure 6. Thermocouple Bead Covered with Epoxy**



9. Add other tack-downs of epoxy along the length of wire to provide strain relief for the thermocouple wire. Remove any small epoxy dots or lines that have been accidentally added after the epoxy cures.
10. Follow the epoxy manufacturer's instructions for curing the epoxy. If an oven is used for curing the epoxy, ensure the vibration in the oven is minimal to prevent the thermocouple bead from moving and losing intimate contact with the IHS.
11. Once the epoxy has cured, remove all tape and check for any epoxy residual outside the thermocouple attach area. Run the tip of your finger around the IHS surface to find any small epoxy dots. Remove the non-necessary epoxy residual completely so it does not impact heatsink to IHS mating surface. Clean the IHS surface after conducting this finger test.
12. **Check for electrical continuity between the thermocouple and the IHS again.** If there is no electrical continuity between the thermocouple and the IHS, repeat Steps 4–12.

### 2.3.3.2 Heatsink Preparation – Rectangular (Cartesian) Geometry

To measure the case temperature, a heatsink must be mounted on the processor to dissipate the heat to the environment. The heatsink base must be grooved to allow a thermocouple to be routed from the center of the heatsink without altering the IHS for heatsink attachment. The groove in the heatsink has two features. The first is a 0.180 inch diameter relief for the thermocouple bead and surrounding epoxy. The second feature is a 0.040 inch-wide groove that allows the thermocouple wire to be routed to the edge of the IHS/heatsink assembly. The relief and wire routing groove should be deep enough to avoid significant impact on heatsink performance, while minimizing interference between thermocouple and the heatsink base. Groove depth should be 0.025 to 0.040 inches maximum [0.6 to 1.0 mm]. Notice the center of the thermocouple bead relief is located 0.050 inches from the centerline of the heatsink. An example of a grooved heatsink base is shown in Figure 7. It must be noted that the center of the circle area needs to be located 0.05 inches off center from the location corresponding to the thermocouple bead at the center of the IHS. This offset accommodates the bead of epoxy that covers both the thermocouple and thermocouple wires.

Figure 7. Grooved Heatsink Bottom

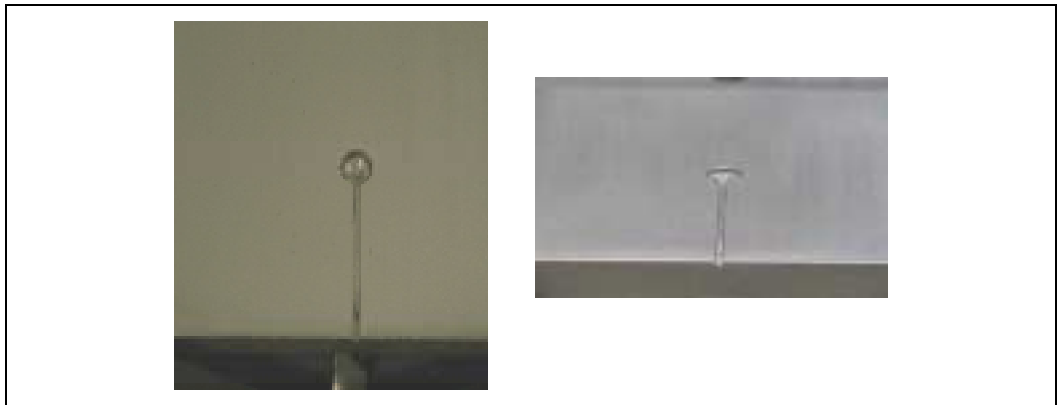
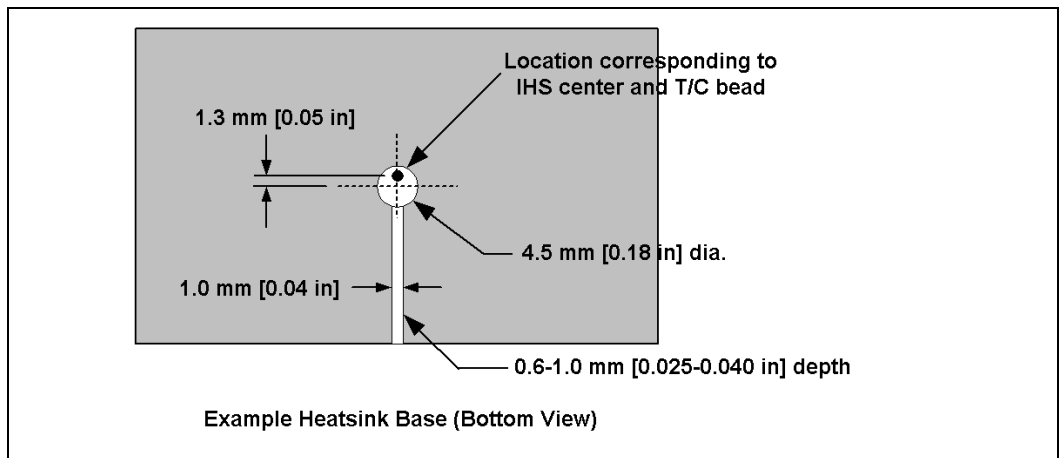


Figure 8. Heatsink Bottom Groove Dimensions



**NOTES:**

1. Applies to rectangular or cylindrical heatsink base
2. All units are in inches. The groove (including the circle area) depth is 0.025 to 0.040 inches max.





### 2.3.3.3 Heatsink Preparation – Radial (Cylindrical) geometry

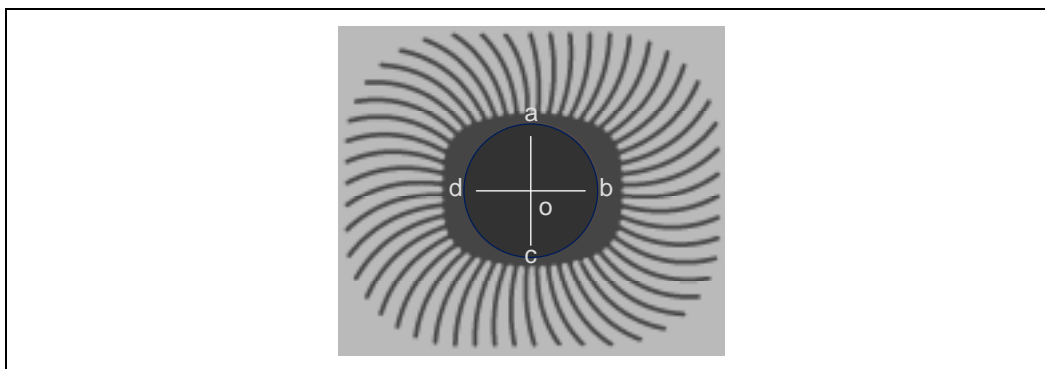
For some heatsinks that have a radial geometry (see Figure 9), it may be necessary to locate the center of the heatsink using features in the fin pattern.

For example, the 52-fin radial heatsink of the Intel reference design for the Intel® Pentium® 4 processor in the 478-pin package (refer to section 3.3 and Figure 19) requires the following procedure:

1. Identify fin gap (a) as shown in Figure 9.
2. Count 13 fin gaps in clockwise direction; identify fin gap (b).
3. Repeat for fin gap (c) and fin gap (d).
4. Scribe lines (a-c) and (b-d) across the core area of the radial heatsink.
5. Locate heatsink center at the intersection of lines (a-c) and (b-d).
6. Machine a groove 0.040 inches wide, 0.025 to 0.040 inches deep along line (o-a).
7. Locate the center for the circle area 0.050 inches off the heatsink centerline, along line (o-a).
8. Machine the circle area 0.180 inches diameter, 0.025 to 0.040 inches deep to accommodate the thermocouple and epoxy bead.

**Note:** This procedure takes into account the fact that the center of the IHS and the center of the heatsink coincide for this particular design.

**Figure 9. Radial Heatsink Geometry**



### 2.3.3.4 Thermal Measurement

1. Attach a thermocouple at the center of the package (IHS-side) using the proper thermocouple attach procedure (refer to Section 2.3.3.1).
2. Connect the thermocouple to a thermocouple meter.
3. Mill groove on heatsink base (refer to Section 2.3.3.2 or to Section 2.3.3.3).
4. Apply thermal interface material to either IHS top surface or on the surface of heatsink base.
5. Mount the heatsink to the processor package with the intended heatsink attach clip and all relevant mechanical interface components (e.g. retention mechanism, processor EMI attenuation solutions, etc.).



6. Refer to section 2.3.2 to setup the thermocouples used for  $T_A$  measurement, and connect them to a thermocouple meter.
7. Depending on the overall experimental setup, the time needed to have stable thermal conditions may vary.  $T_A$  and  $T_C$  measurements are valid once constant (refer to section 2.3.4.3) for application to the thermal test vehicle).

**Note:** This methodology requires special care when assembling the grooved heatsink on top of the IHS with the thermocouple attached. Mismatch between the heatsink groove and the thermocouple wires and bead may lead to inaccurate measurements, and even thermocouple damage, in particular when compressive load is required to get better performance out of the thermal interface material.

## 2.3.4 Thermal Test Vehicle Information

The Intel® Pentium® 4 processor in the 478-pin package Thermal Test Vehicle (TTV) is a FC-PGA2 package assembled with a thermal test die.

Cooling solution performance should be characterized or validated using the TTV only. Only the TTV provides a well-characterized tool suitable for thermal testing. TTV. It also allows simulating processor thermal targets before the parts are available. The correction factor of the TTV to real processors, given Table 2 below, is then used to define the performance of the solution on real processor.

The part number for the TTV is A47244-01.

The TTV can also be identified by the topside marking: ITVN1 THERM SAMP.

### 2.3.4.1 Thermal Test Die

A resistance-type heater band covers nearly the entire surface area of the test die and is used to simulate the heat generation on the die.

The room temperature resistance of the heater is about  $60 \Omega$ ,  $\pm 5\%$ . This resistance value will increase as the die temperature increases at a rate of about  $0.10 \Omega/^\circ\text{C}$ .

### 2.3.4.2 Connections

The heater is connected to external pins so that it can be powered by an external DC power supply. The resistance heater of the thermal die is terminated at the power and ground pins of the package. The power and ground pin-out of the TTV match the power and ground pin-out of the actual processor. Therefore the TTV can be plugged into any motherboard that has been designed for the Intel Pentium 4 processor in the 478-pin package.

The heater can be accessed by de-populating the power decoupling capacitors and attaching wires to the power and ground sides of one of the capacitor. It is recommended that all decoupling capacitors be removed because the high voltages required for the TTV may exceed the maximum voltage rating of the capacitors. The voltage regulator inductors should also be removed to isolate the VR from the TTV power supply. Motherboard designs vary; therefore, an optimal location to tap into power should be chosen by the user.



The recommended DC-power supply rating is listed in Table 1. The power supply should be able to deliver more current if necessary to cover for die resistance variations.

**Table 1. Recommended DC Power Supply Ratings**

Target Die Power Level	Power Supply Rating
20 W	40 V and 1 A
25 W	45 V and 1 A
30 W	45 V and 1 A
35 W	50 V and 1 A
40 W	55 V and 1 A
50 W	60 V and 1.5 A
60 W	65 V and 1.5 A
70 W	70 V and 1.5 A
75 W	75 V and 1.5 A

The power dissipation should be maintained below 75 W and the IHS temperature should be maintained to less than 80°C during the thermal testing. By violating the constraints, the TTV lifetime will be reduced. It must be noted that the reliability of TTV is limited and the TTV is not designed for long-term testing purposes.

**Note:** The heaters on the thermal testing devices are metal resistors. The polarity does not matter: Positive and negative terminals are interchangeable.

**Note:** TTV is not sensitive to static electricity.

### 2.3.4.3 Thermal Measurements

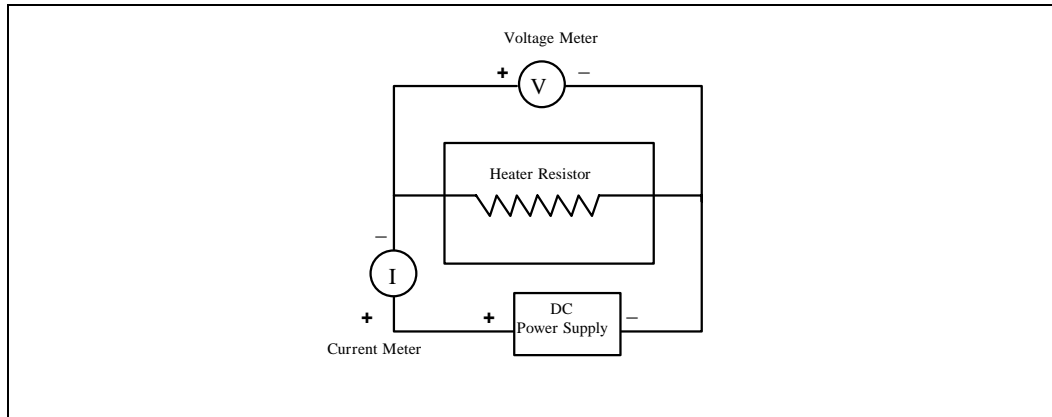
Refer to Section 2.3.2 for  $T_A$  measurement methodology. Refer to Section 2.3.3.1 for thermocouple attachment to the IHS and to Section 2.3.3.2 and Section 2.3.3.3 for the heatsink preparation.

For the thermal measurement itself, use the following instructions for the TTV, instead of the generic instructions given in Section 2.3.3.4:

1. Measure the resistance of the heater resistor of TTV at the room temperature to check for the reasonable readings. If reasonable reading of  $\sim 60 \Omega$  is not obtained, either the TTV is damaged or the wire connection is not correct. In case the shortage occurs between the positive and negative terminals, do not perform the test as damage could occur to the power supplier.
2. Attach a thermocouple at the center of the package (IHS-side) using the proper thermocouple attach procedure.
3. Connect the thermocouple to a thermocouple meter.
4. Mill groove on heatsink base, as recommended in Section 2.3.3.2 and Section 2.3.3.3.
5. Apply thermal interface materials to either IHS top surface or on the surface of heatsink base.
6. Mount the heatsink to the TTV with the intended heatsink attach clip and all relevant mechanical interface components (e.g., retention mechanism, processor EMI attenuation solutions, etc.).
7. Place the TTV in the test environment (e.g., a wind tunnel or a computer chassis).

8. Connect the heater resistor of TTV to a DC power supply. Connect current and voltage meters as shown in the following figure.

**Figure 10. Electrical Connection for Heater**



9. Refer to section 2.3.2 to setup the thermocouples used for  $T_A$  measurement, and connect them to a thermocouple meter.
10. Set the voltage of the DC power supply to the value calculated from the targeted power level and the heater resistance, if the DC-power supplier uses a voltage-control mode (e.g.,  $\text{Voltage} = \sqrt{\text{Heater Resistance} \times \text{Power}}$ ). Alternatively, an appropriate current can be set to the DC-power supplier if the DC-power supplier uses a current-control mode.
11. The actual power applied to the heater resistor can be calculated by multiplying the readings from the voltage meter and the current meter as shown in the figure in Step 8. As the heater heats up, the heater resistance will increase slightly and the current will decrease resulting in a small drop of power if a voltage-control mode is used. The power supply voltage has to be increased to compensate for the drop in the current to maintain a constant power. Wait for one hour to reach the stable condition before reading the case temperature ( $T_C$ ) and the local ambient temperature ( $T_A$ ) from the thermocouples.
12. Calculate the case-to-ambient thermal relation resistance ( $\theta_{CA}$ ) based on equation 1 given in Section 2.2.2.2. This equation is shown below.

$$\theta_{CA} = (T_C - T_A) / P_D$$

#### 2.3.4.4 TTV Correction Factor to the Intel® Pentium® 4 Processor in the 478-Pin Package

Correction factors usually need to be applied to predict the thermal solution performance on the real parts from thermal performance measured on a thermal test vehicle. Table 2 provides these correction factors in the case of the TTV and the Intel® Pentium® 4 processor in the 478-pin package, and of the TTV. The value of a thermal resistance is derived from the value measured on the TTV and the corresponding correction factor according to equation

$$\{\text{Processor } \theta_{CA}\} = \{\text{TTV } \theta_{CA}\} \times \text{Correction factor}$$

This formula transposes to  $\theta_{CS}$  and  $\theta_{SA}$ .



Table 2. TTV Correction Factors

Thermal Resistance	Intel® Pentium® 4 Processor in the 478-Pin Package	Intel® Pentium® 4 Processor with 512KB L2 Cache on .13 Micron Process
$\Theta_{CS}$	0.948	1.151
$\Theta_{SA}$	0.999	1.014
$\Theta_{CA}$	0.985	1.053

$\Theta_{CA}$  correction factors should be used for the reference thermal design described in Chapter 3, or when the ratio  $\Theta_{CS}/\Theta_{SA}$  is similar to this design (~ 0.53 for the Intel® Pentium® 4 processor with 512KB L2 cache on .13 micron process and ~0.6 for the Intel Pentium 4 processor in the 478-pin package). If this ratio is significantly different then it is recommended to use individual  $\Theta_{CS}$  and  $\Theta_{SA}$  correction factors and add corrected  $\Theta_{CS}$  and  $\Theta_{SA}$  to get  $\Theta_{CA}$ .

## 2.4 Thermal Management Logic and Thermal Monitor Feature

### 2.4.1 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 for example, the average power dissipation can drop by up to 50%. Note that the processor performance also drops by about 50% during this period, since program execution halts while the clocks are removed. Varying the duty cycle has a corresponding influence on power dissipation and processor performance. The duty cycle is specific to the processor (typically 30-50%).

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 external thermocouples connected to the processor package to monitor and control a thermal management solution has some inherent disadvantages. Thermal conductivity through the processor package creates a temperature gradient between the processor case and silicon. This temperature difference may be large with the silicon temperature always being higher than the case temperature. Since thermocouples measure case temperature, not silicon temperature, significant



added margin may be necessary to ensure the processor silicon does not exceed its maximum specification (i.e., clock modulation may have to be turned on when the case temperature is significantly below its maximum specification to ensure the processor does not overheat). This added margin might 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 may occur in the course of normal operation. With this type of thermal characteristic, it would not be possible to control fans or other cooling devices based on processor case temperature. By the time the fans have spun up to speed, the processor may be well beyond a safe operating temperature. Just as large added margins would be necessary to account for package thermal gradients, large margins would also be necessary if temperature-controlled fans were implemented.

An on-die thermal management feature called Thermal Monitor is available on the Intel® Pentium® 4 processor in the 478-pin package. It provides a thermal management approach to support the continued increases in processor frequency and performance. It resolves the issues discussed above so that external thermocouples are no longer needed. By using a highly accurate on-die temperature sensing circuit and a fast acting temperature control circuit, the processor can rapidly initiate thermal management control. As a result, added thermal margins can be significantly reduced and the resulting system performance impact can be minimized if not eliminated.

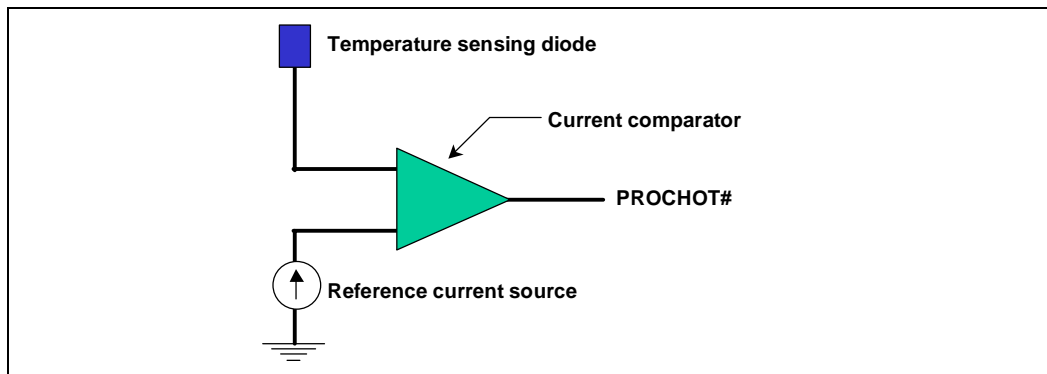
## 2.4.2 Thermal Monitor Implementation

On the Intel® Pentium® 4 processor in the 478-pin package, the Thermal Monitor is integrated into the processor silicon. The Thermal Monitor includes:

- A highly accurate on-die temperature sensing circuit
- A signal (PROCHOT#) that indicates the processor has reached its maximum operating temperature
- A thermal control circuit that can reduce processor temperature by controlling the duty cycle of the processor clocks
- Registers to determine the processor thermal status.

The processor temperature is determined through an analog thermal sensor circuit comprised of a temperature sensing diode, a factory calibrated reference current source, and a current comparator (See Figure 11). A voltage applied across the diode induces 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 11. Thermal Sensor Circuit



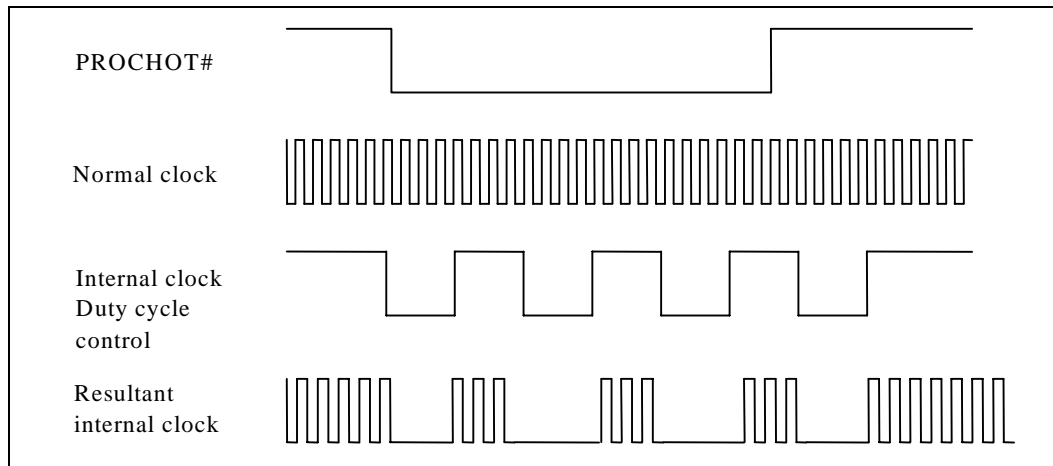
The PROCHOT# signal is available internally to the processor as well as externally. External indication of the processor temperature status is provided through the bus signal PROCHOT#. When the processor temperature reaches the trip point, PROCHOT# is asserted. When the processor temperature is below the trip point, PROCHOT# is deasserted. Assertion of the PROCHOT# signal is independent of any register settings within the processor. It is asserted any time the processor die temperature reaches the trip point. The point where the thermal control circuit goes active is set to the same temperature at which the processor is tested.

The Thermal Monitor's thermal control circuit (TCC), when active, lowers the processor temperature by reducing the duty cycle of the internal processor clocks. The thermal control circuit portion of the Thermal Monitor must be enabled by the system BIOS for the processor to be operating within specifications. When active, the TCC turns the processor clocks off and then back on with a predetermined duty cycle. The actual duty cycle varies from one product to another. Refer to Figure 12 for an illustration. Cycle times are processor speed dependent and decrease as processor core frequencies increase.

Performance counter registers, status bits in model specific registers (MSRs), and the PROCHOT# output pin are available to monitor and control the Thermal Monitor behavior. Details regarding the use of these registers are described in the *IA-32 Intel Architecture Software Developer's Manual: Volume III System Programming Guide*.

In addition to the Thermal Monitor, the processor clocks can also be modulated via an ACPI register that is implemented as an MSR on the processor core. This is referred to as 'on demand mode' clock modulation. See section 2.4.3 for additional details.

**Figure 12. Concept for Clocks under Thermal Monitor Control**



### 2.4.3 Operation and Configuration

To maintain compatibility with previous generations of processors, which have no integrated thermal logic, the thermal control circuit 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 *IA-32 Intel Architecture Software Developer's Manual: Volume III System Programming Guide* for specific 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 the 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, processor power consumption will be reduced within a few hundred clock cycles after the thermal sensor detects a high temperature (i.e., within a few hundred clock cycles of PROCHOT# assertion). 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 MSRs. The MSRs may be set based on a particular system event (e.g., an interrupt generated after a system event), or may be set at any time through the operating system or custom driver control thus forcing the thermal control circuit on. This is referred to as “on-demand” mode. 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 period the clocks are disabled is ~3 μs. This time period is frequency dependent, and decreases as frequency increases. To achieve different duty cycles, the



length of time that the clocks are disabled remains constant, and the time period that the clocks are enabled is adjusted to achieve the desired ratio. For example, if the clock disable period is 3  $\mu\text{s}$ , and a duty cycle of  $\frac{1}{4}$  (25%) is selected, the clock on time would be reduced to approximately 1  $\mu\text{s}$  [on time (1  $\mu\text{s}$ )  $\div$  total cycle time (3 + 1)  $\mu\text{s}$  =  $\frac{1}{4}$  duty cycle]. Similarly, for a duty cycle of  $\frac{7}{8}$  (87.5%), the clock on time would be extended to 21  $\mu\text{s}$  [21  $\div$  (21 + 3) =  $\frac{7}{8}$  duty cycle].

In a high temperature situation, if the thermal control circuit and ACPI MSR (automatic and on-demand modes) are used simultaneously, the fixed duty cycle determined by automatic mode would take precedence.

## 2.4.4 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 Monitor and thermal control circuit to be enabled for all Intel® Pentium® 4 processor in the 478-pin package based systems.* At a minimum, the thermal control circuit supplies an added level of protection against processor over-temperature failure.

To minimize the cost of a processor thermal solution, system designers are encouraged to take advantage of the Thermal Monitor feature capability. The Thermal Monitor feature allows processor thermal solutions to design to the thermal design power (TDP) target, as opposed to maximum processor power consumption. Designing to the lower TDP target results in a lower thermal solution cost, while still maintaining a level of processor performance that is virtually indistinguishable from systems designed to manage maximum power dissipation levels.

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

The processor thermal design power (TDP) is based on measurements of processor power consumption while running various high power applications. This data is used to determine those applications that are interesting from a power perspective. These applications are then evaluated in a controlled thermal environment to determine their sensitivity to activation of the thermal control circuit. This data is used to derive the TDP targets published in the processor datasheet.

A system designed to meet the TDP and  $T_c$  targets published in the processor datasheet greatly reduces the probability of real applications causing the thermal control circuit to activate under normal operating conditions. Systems that do not meet these specifications could be subject to more frequent activation of the thermal control circuit depending upon ambient air temperature and application power profile. Moreover, if a system is significantly under designed, there is a risk that the Thermal Monitor feature will not be capable of maintaining a safe operating temperature and the processor could shutdown and signal THERMTRIP#.

For information regarding THERMTRIP#, refer to Section 2.4.6.2 and to the processor datasheet.



## 2.4.5 Operating System and Application Software Considerations

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

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 *IA-32 Intel Architecture Software Developer's Manual: Volume III System Programming Guide* 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\* 98SE and Windows\* 2000 use non-execution based calibration loops and therefore should 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.

## 2.4.6 Legacy Thermal Management Capabilities

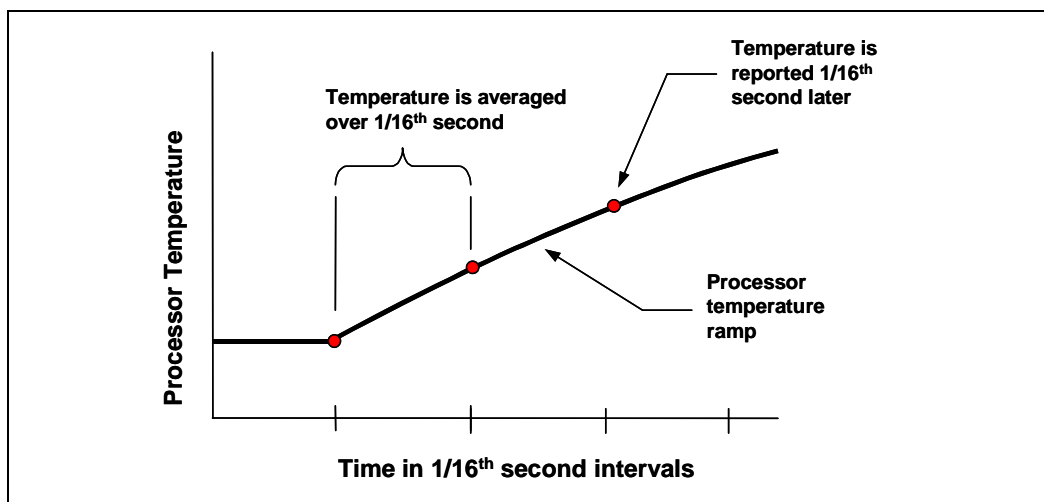
In addition to Thermal Monitor, the Intel® Pentium® 4 processor in the 478-pin package supports the same thermal management features as available on the Intel Pentium III processor. These features are the on-die thermal diode and THERMTRIP# signal for indicating catastrophic thermal failure.

### 2.4.6.1 Thermal Diode

The Intel Pentium 4 processor in the 478-pin package 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 the thermal control circuit. As mentioned earlier, the processor 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 1/8<sup>th</sup> (0.125 sec) second time period, the temperature is averaged over 1/16<sup>th</sup> of a second. In a scenario where the silicon temperature ramps at 50 °C/sec, or approximately 6°C/0.125 sec, the processor will be ~4.5 °C above the temperature reported by the thermal sensor. (Change in diode temperature averaged over 1/16<sup>th</sup> seconds = ~1.5°C; temperature reported 1/16<sup>th</sup> second later at 1/8<sup>th</sup> second when the actual processor temperature would be 6°C higher, see Figure 13).

Figure 13. Thermal Diode Sensor Time Delay



### 2.4.6.2 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# goes active and power needs to be removed from the processor. THERMTRIP# stays active until RESET# has been initiated. THERMTRIP# activation is independent of processor activity and does not generate any bus cycles. Refer to the processor datasheet for more information about THERMTRIP#.

### 2.4.6.3 Thermal Measurement Correlation

There are two independent thermal diodes in the Intel® Pentium® 4 processor in the 478-pin package. One is the on-die thermal diode described in Section 2.4.6.1. The other is in the temperature sensor used for the Thermal Monitor and for THERMTRIP#. The Thermal Monitor's temperature sensor and the on-die thermal diode are independent and isolated devices with no direct correlation to one another. Circuit constraints and performance requirements prevent the Thermal Monitor's temperature sensor and the on-die thermal diode from being located at the same place on the silicon. As a result, it is not possible to predict the activation of the thermal control circuit by monitoring the on-die thermal diode.

### 2.4.7 Cooling System Failure Warning

If desired, the system may be designed to cool the maximum processor power. 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 the 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.



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# 3 Critical to Function Dimensions of Intel Reference Cooling Solution

## 3.1 Intel Validation Criteria for the Reference Design

### 3.1.1 Heatsink Performance

#### 3.1.1.1 Reference Heatsink Performance Target

The Intel reference heatsink is identical for the Intel® Pentium® 4 processor in the 478-pin package and the Intel® Pentium® 4 processor with 512KB L2 cache on .13 micron process. The reference heatsink performance targets are given in Table 3. Performance difference is expected when this heatsink is attached to either processor package: differences in the die size and power density between both processors changes the heat spreading through the IHS.

Assuming a  $T_A$  at the processor fan heatsink inlet of 45°C, the performance targets given below support published frequencies for the Intel Pentium 4 processor in the 478-pin package up to 2GHz, as well as the Intel Pentium 4 processor with 512KB L2 cache on the .13 micron process at the published frequencies. Refer to the processor datasheet for additional information.

**Table 3. Reference Heatsink Performance Target**

Processor	Thermal Performance, $\theta_{ca}$ (Mean + 3 $\sigma$ )	Details
Intel® Pentium® 4 Processor in the 478-Pin Package	0.40 °C/W (target)	TIM = Chomerics* T454 Nominal clip load = 75 lbf
Intel® Pentium® 4 Processor with 512KB L2 Cache on .13 Micron Process	0.43 °C/W (target)	TIM = Chomerics* T454 Nominal clip load = 75 lbf

#### 3.1.1.2 Altitude

The reference heatsink solutions will be evaluated at sea level. However, many companies design products that must function reliably at high altitude, typically 1,500 m (5,000 ft) or more. Air-cooled temperature calculation and measurement at sea level must be adjusted to take into account altitude effects like variation in air density and overall heat capacity. This often leads to some degradation in thermal solution performance compared to what is obtained at sea level, with lower fan performance and higher surface temperatures. The system designer needs to account for this altitude effects in the overall system thermal design to make sure that the  $T_C$  requirement for the processor is met at the targeted altitude.



### 3.1.1.3 Reference Heatsink Thermal Validation

The Intel reference heatsink is validated within specific boundary conditions based on the methodology described section 2.3, and using a thermal test vehicle (refer to section 2.3.4).

Testing is done on bench top test boards at ambient lab temperature. In particular, for the reference heatsink, the Plexiglas\* barrier is installed 3 inches above the motherboard (refer to section 2.3.2).

The test results are reported in terms of performance on real parts (using the thermal test vehicle correction factor), and of mean + 3 $\sigma$  value.

## 3.1.2 Fan Performance for Active Heatsink Thermal Solution

The fan power requirement for proper operation is a maximum current of 740 mA at 12 V.

For active thermal solutions, the fan should demonstrate a functional lifetime of 40,000 hours. In addition, the fan should demonstrate performance to the reliability criteria outlined in Table 4.

**Table 4. Fan Performance Recommendation**

Test	Requirement	Pass/Fail Criteria
Thermal Cycling	-5 °C to +70 °C, 500 cycles	visual check <sup>1</sup> RPM check <sup>2</sup>
Humidity	85% relative humidity / 55 °C, 1000 hours	visual check <sup>1</sup> RPM check <sup>2</sup>
Power Cycling	7,500 on/off cycles with each cycle specified as 3 minutes on, 2 minutes off 70 °C	visual check <sup>1</sup> RPM check <sup>2</sup>

**NOTES:**

1. Visual check: Labels, housing and connections are all intact.
2. RPM check: No fan RPM changes of greater than 20%, following test.

### 3.1.3 Structural Reliability of Thermal Solution Assembly

Structural reliability tests consist of unpackaged, board-level vibration and shock tests of a given thermal solution in assembled state. The thermal solution should be capable of sustaining thermal performance after these tests are conducted; however, the conditions of the tests outlined here may differ from your own system requirements.

#### 3.1.3.1 Test Sequence

Each test sequence should start with components (i.e. motherboard, heatsink assembly, etc.) that have never been previously submitted to any reliability testing.

The test sequence should always start with a visual inspection after assembly, and BIOS/CPU/Memory test (refer to section 3.1.3.5 below). The stress test should be then followed by a visual inspection and then BIOS/CPU/Memory test.

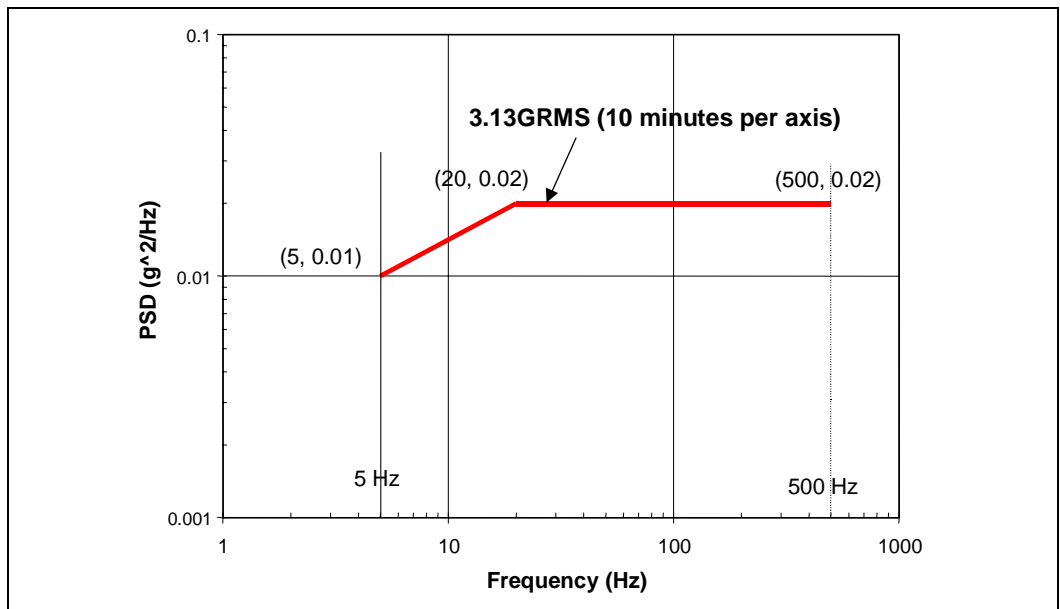
#### 3.1.3.2 Random Vibration Test Procedure

Duration: 10 min/axis, 3 axes

Frequency Range: 5 Hz to 500 Hz

Power Spectral Density (PSD) Profile: 3.13 g RMS

Figure 14. Random Vibration PSD



### 3.1.3.3 Shock Test Procedure

Recommended performance requirement for a motherboard:

- Quantity: 3 drops for + and - directions in each of 3 perpendicular axes (i.e., total 18 drops).
- Profile: 50 G trapezoidal waveform, 11 ms duration, 170 in./sec minimum velocity change.
- Setup: Mount sample board on test fixture.

Figure 15. Shock Acceleration Curve



### 3.1.3.4 Post-Test Pass Criteria

The post-test pass criteria are:

1. No significant physical damage to the retention mechanism windows, including any indication of shearing, cracks in the retention mechanism body, or evidence of significant clip lever penetration into the fan shroud.
2. Clip must remain latched to retention mechanism windows.
3. Heatsink remains seated and its bottom remains mated flatly against processor die surface. No visible gap between the heatsink base and processor IHS. No visible tilt of the heatsink with respect to the retention mechanism.
4. No signs of physical damage on motherboard surface due to impact of heatsink or heatsink attach clip.
5. No visible physical damage to the processor package.
6. Successful BIOS/Processor/memory test of post-test samples.
7. Thermal compliance testing to demonstrate that the case temperature specification can be met.





### 3.1.3.5 Recommended BIOS/CPU/Memory Test Procedures

This test is to ensure proper operation of the product before and after environmental stresses, with the thermal mechanical enabling components assembled. The test shall be conducted on a fully operational motherboard that has not been exposed to any battery of tests prior to the test being considered.

Testing setup should include the following components, properly assembled and/or connected:

- Appropriate system motherboard
- Processor
- All enabling components, including socket and thermal solution parts
- Power supply
- Disk drive
- Video card
- DIMM
- Keyboard
- Monitor

The pass criterion is that the system under test shall successfully complete the checking of BIOS, basic processor functions and memory, without any errors. *Intel PC Diags* is an example of software that can be utilized for this test.

### 3.1.4 Material and Recycling Requirements

Material shall be resistant to fungal growth. Examples of non-resistant materials include cellulose materials, animal and vegetable based adhesives, grease, oils, and many hydrocarbons. Synthetic materials such as PVC formulations, certain polyurethane compositions (e.g., polyester and some polyethers), plastics which contain organic fillers of laminating materials, paints, and varnishes also are susceptible to fungal growth. If materials are not fungal growth resistant, then MIL-STD-810E, Method 508.4 must be performed to determine material performance.

Material used shall not have deformation or degradation in a temperature life test.

Any plastic component exceeding 25 grams must be recyclable per the European Blue Angel recycling standards.



### 3.1.5 Safety Requirements

Heatsink and attachment assemblies shall be consistent with the manufacture of units that meet the safety standards:

- UL Recognition-approved for flammability at the system level. All mechanical and thermal enabling components must be a minimum UL94V-2 approved.
- CSA Certification. All mechanical and thermal enabling components must have CSA certification.
- Heatsink fins must meet the test requirements of UL1439 for sharp edges.

## 3.2 Enabling Component Mechanical Envelope

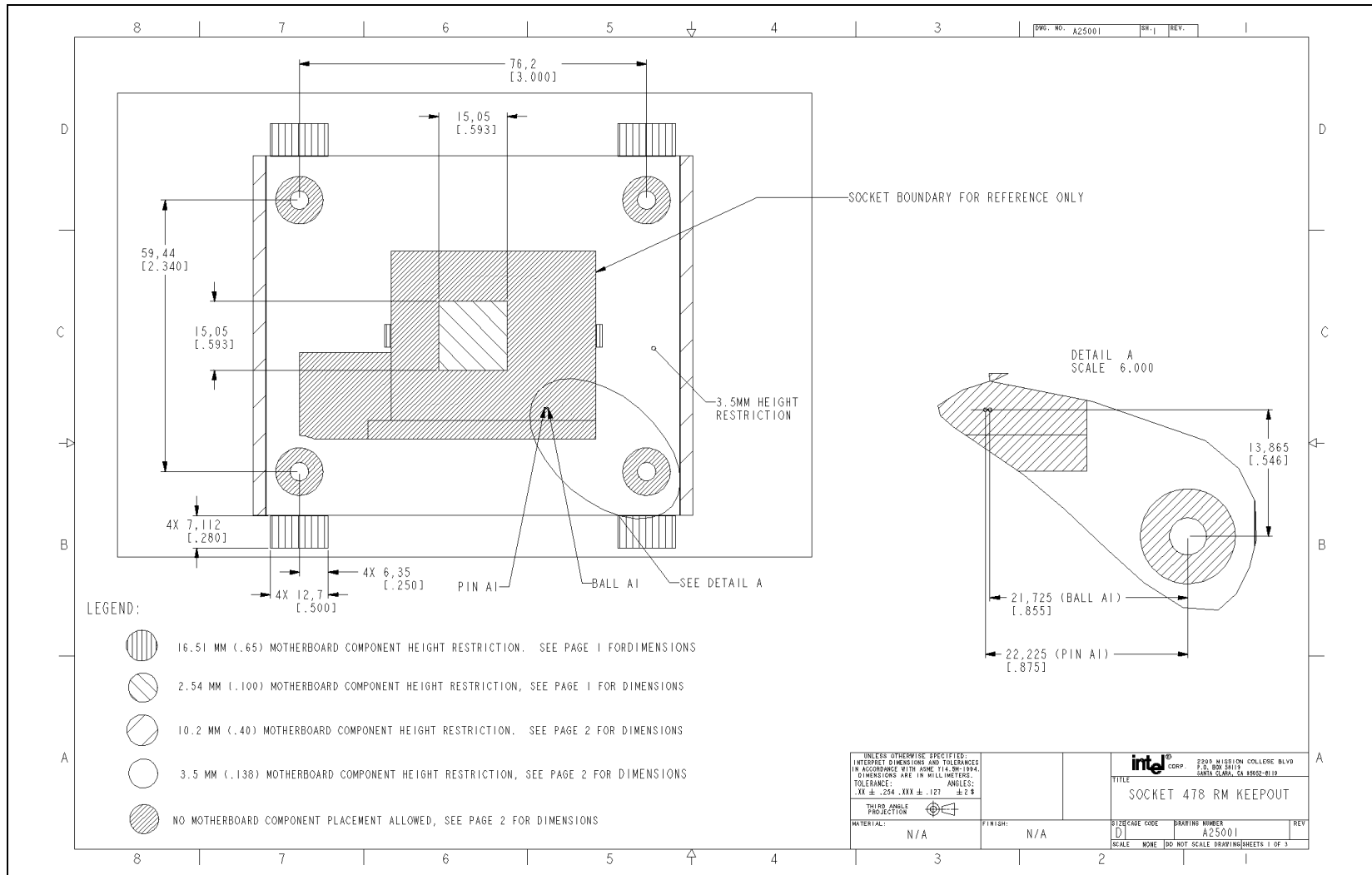
Figure 16, Figure 17, and Figure 18 show the overall keep-out and keep-in dimensions for the reference thermal/mechanical enabling design.

Figure 16 and Figure 17 show the motherboard keep-outs and height restrictions under the enabling component region. Figure 18 shows the overall volumetric keep-in for the enabling component assembly. This volumetric space encapsulates the processor, the socket, and the entire thermal/mechanical enabling solution (for example, for the reference design this includes: fan heatsink assembly, retention mechanism, and attach clips). The maximum allowable volume for the fan/heatsink assembly is defined in Section 3.3.2.

**Note:** Pin A1 and Ball A1, as referred to in Figure 16, do not physically exist on the 478-pin package and the 478-pin socket respectively. However, they may be used as a reference for design purposes. Motherboard designers should focus exclusively on Ball A1 callouts to determine position of the hole relative to the socket when working of the board layout. By design, the processor is then centered within the hole pattern when the socket is in the closed position. Pin A1 is associated specifically with the package, and its position on the drawing Figure 16 corresponds to the package within the socket in close position.



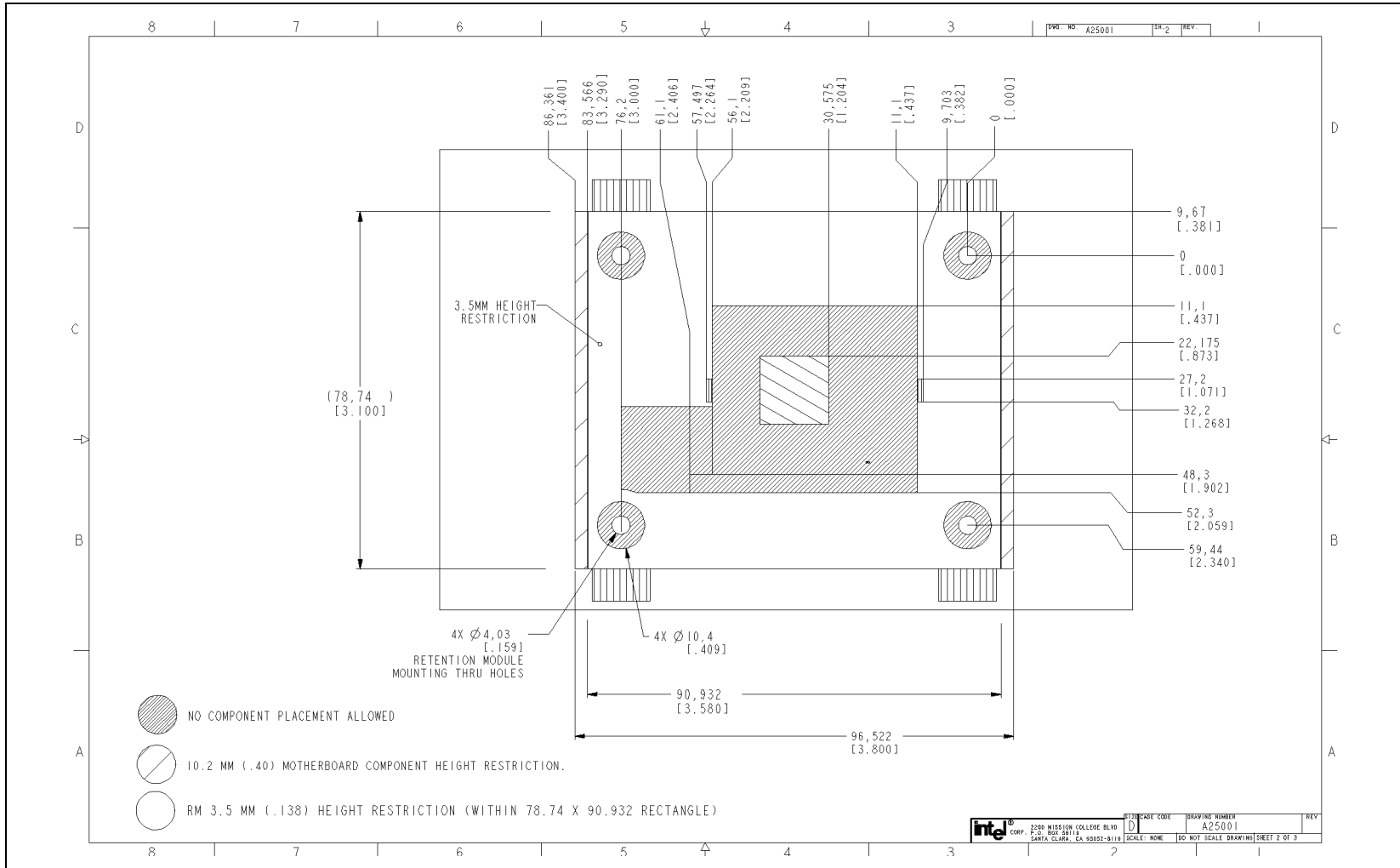
Figure 16. Motherboard Keep-out Footprint Definition and Height Restrictions for Enabling Components – 1



NOTE: Length in mm (inches)



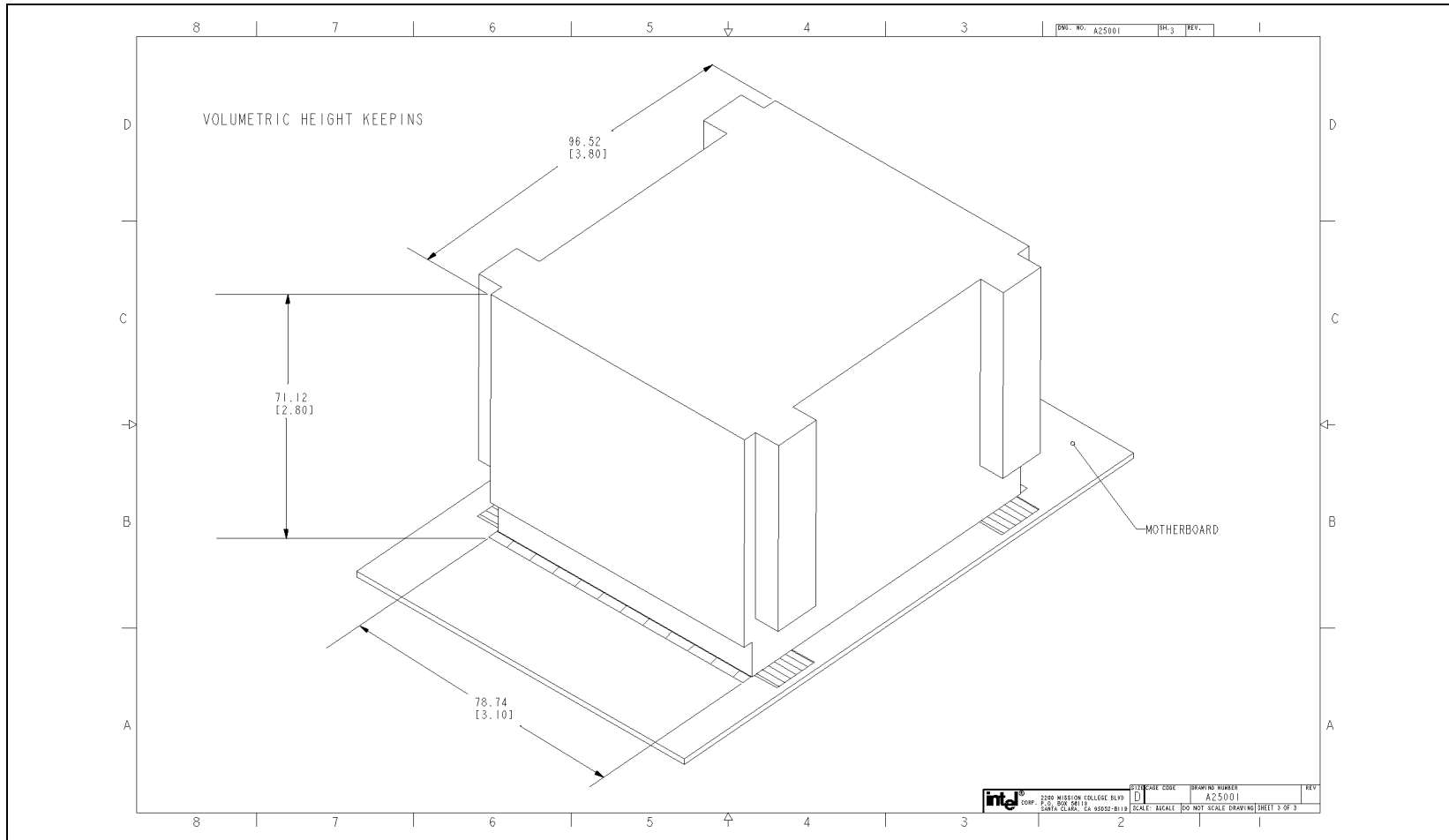
Figure 17. Motherboard Keep-out Footprint Definition and Height Restrictions for Enabling Components – 2



NOTE: Length in mm (inches)



Figure 18. Volumetric Keep-in for Enabling Components



**NOTES:**

1. Length in mm (inches)
2. Cooling Reference Solution for the Intel® Pentium® 4 Processor in the 478-Pin Package

### 3.3 Reference Solution for the Intel® Pentium® 4 Processor in the 478-Pin Package

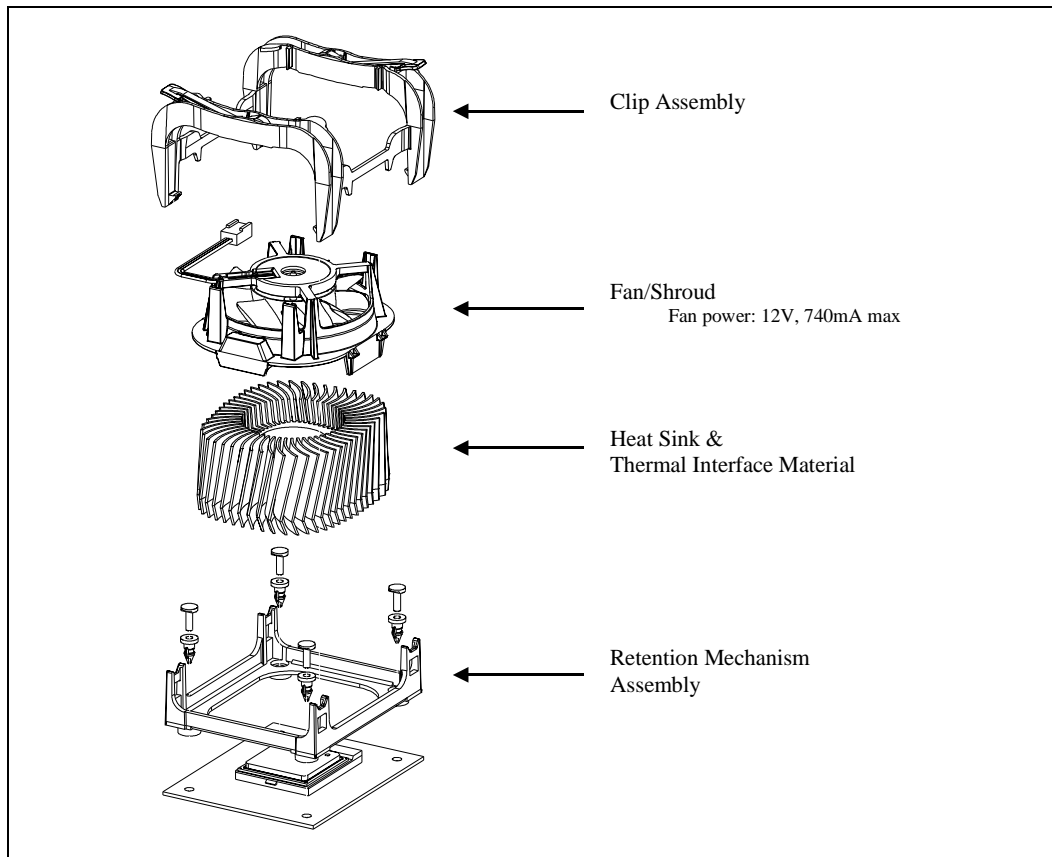
**Note:** The thermal mechanical reference design for the Intel® Pentium® 4 in the 478-pin package has been validated according to the Intel validation criteria given in Section 3.1, and using all the reference components as described in this document along with the reference thermal mechanical enabling components for the chipset. Any thermal mechanical design using some of the reference components in combination with any other thermal mechanical solution needs to be fully validated according to the customer criteria. Also, if customer thermal mechanical validation criteria differ from the Intel criteria, the reference solution should be validated against the customer criteria.

#### 3.3.1 Components

Figure 19 shows an exploded view of the Intel reference solution for the Intel Pentium 4 processor in the 478-pin package. This reference solution consists of: heatsink, fan, fan shroud, thermal interface material, heatsink clip, retention mechanism.

**Note:** Intel reserves the right to make changes and modifications to the design as necessary.

**Figure 19. Exploded View of the Thermal Mechanical Enabling Assembly for the Processor**



### 3.3.2 Heatsink Mechanical Design Guidelines

This section defines the mechanical requirements for the interface between a processor heatsink /fan /shroud assembly and the reference mechanical components (retention mechanism and clips). These requirements are intended to support interface control in the design of a custom thermal solution.

**Requirement 1:** Heatsink /fan /shroud assembly must stay within the volumetric keep-in defined Figure 20.

*Guideline:* Rectangular heatsink base dimensions and tolerances:

X-dimension =  $2.70 \pm 0.010$  inch

Y-dimension =  $3.28 \pm 0.010$  inch

Z-dimension: Inset in bottom surface of heatsink base in each of four corners should hold a z-dimension of  $0.073 \pm 0.010$  inch.

These dimensions are recommended to limit heatsink movement (rocking and sliding) during lateral shock (x and y directions).

**Requirement 2:** The clip-bearing surface must meet the following specifications to ensure adequate interface with the clip lever through its entire range of motion.

X and Y-dimensions: see Figure 21

Z-dimension: height of bearing surface above bottom surface of heatsink base must be  $1.817 \pm 0.007$  inch

Clip bearing surface roughness must be as defined by SPI B-1 finish or better.

**Requirement 3:** Heatsink /shroud structural characteristics

Vertical load carrying capability: Each of the two clip bearing surfaces must be capable of carrying 70 lb of load oriented in the z-direction. The sub-structure (typically the heatsink) must be capable of receiving this load and transferring it to the heatsink /package interface.

Lateral load carrying capability: The heatsink must be capable of carrying 100 lbs of load in both x and y-directions at the points of contact between the heatsink base and RM.

Stiffness: The structure of the heatsink assembly must have a stiffness equal to or greater than 30,000 lb/in along the z-axis to ensure proper preload induced by the clips.

**Requirement 4:** Max mass and Center of Gravity (CG)

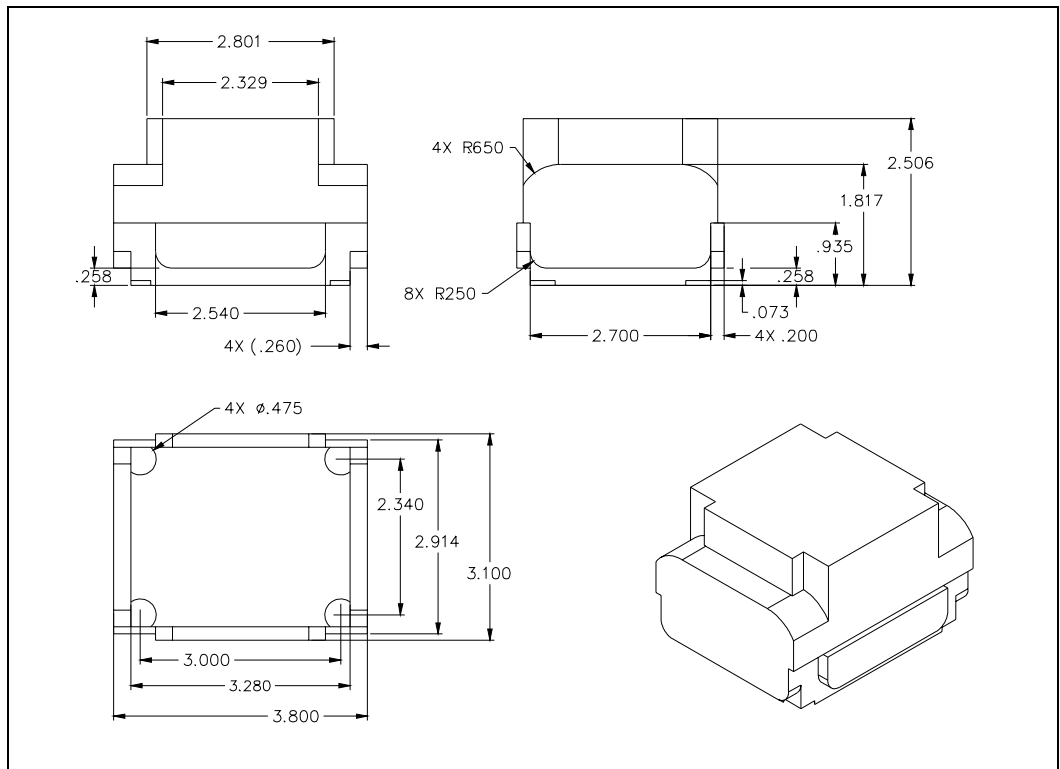
The combined mass of the reference heatsink/fan/shroud assembly is 370 g. The mechanical reference components (retention mechanism and clip) have been validated in mechanical shock and vibration according to the Intel validation criteria defined section 3.1.3 with the reference heatsink. If a cooling solution



based the reference mechanical components uses a heatsink heavier than 370 g, the whole platform should be validated against the customer criteria.

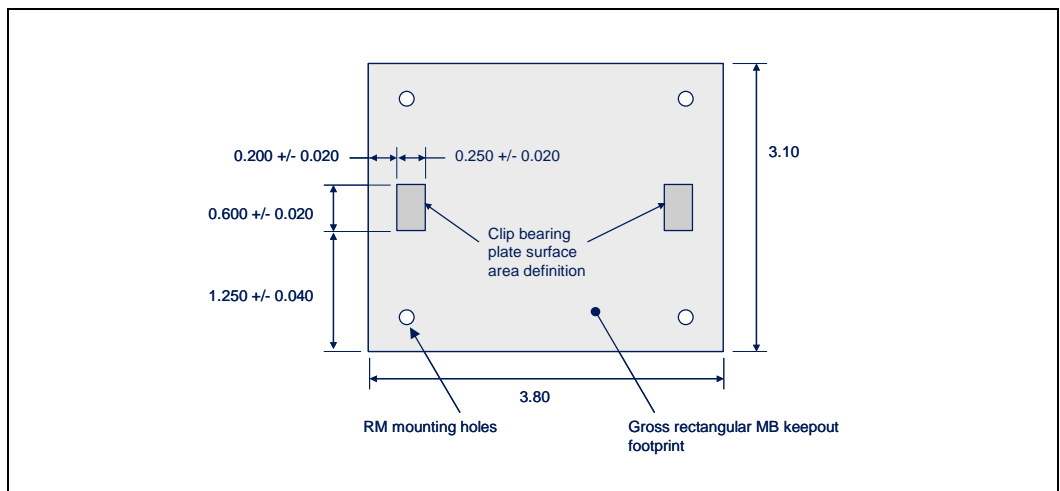
The combined center of gravity of the heatsink /fan /shroud assembly must be no greater than 1.0 inch [25.4 mm] above the top surface of the processor IHS.

**Figure 20. Heatsink, Fan, and Shroud Assembly Volumetric Keep-in**



**NOTE:** All dimensions in inches

**Figure 21. Clip Bearing Surface. Critical X-Y Dimensions and Position**



**NOTE:** All dimensions in inches



### 3.3.3 Reference Heatsink Attach Clip Information

Guidelines for heatsink attach clip are given section 2.1.2. More specifically, the reference heatsink clip for the Intel® Pentium® 4 processor in the 478-pin package is latched to the retention tab features at each corner of the retention mechanism (see reference retention mechanism tab features and reference clip design details in Appendix B).

The reference heatsink attach clip is designed to support the reference heatsink, or heatsinks designed according to the guidelines given section 3.3.2 above.

Intel's target load applied by the clips to the processor heat spreader is  $75 \pm 15$  lbf (maximum load is constrained by the package load capability, described in the processor datasheet). It is normal to observe a bow or bend in the board due to this compressive load on the processor package and the socket. The level of bow or bend depends on the motherboard material properties and component layout. Any additional board stiffening devices (like plates) are not necessary and should not be used along with the reference mechanical components. Using such devices increases the compressive load on the processor package and socket, likely beyond the maximum load that is specified for those components.

Chassis that have adequate clearance between the motherboard and chassis wall (minimum 0.250 inch) should be selected to ensure the board's underside bend does not contact the chassis.

For additional information on the Intel reference mechanical design for the Intel Pentium 4 processor in the 478-pin package, refer to *Mechanical Enabling for the Intel® Pentium® 4 Processor in the 478-Pin Package* document.

### 3.3.4 Thermal Interface Material

The Intel reference design uses a phase change material, T454 from Chomerics\*, as the thermal interface material.

For information on the benefit of the compressive load on the thermal interface material, refer to the *Mechanical Enabling for the Intel® Pentium® 4 Processor in the 478-Pin Package* document.

### 3.3.5 Intel Reference Mechanical Solution Component Drawings

The drawings for the mechanical components of the Intel Reference cooling solution for the Intel Pentium 4 processor in the 478-pin package are given in Appendix B. These mechanical components are meant to interface with the Intel reference fan heatsink (radial bent fin active heatsink), or any solution that complies with the mechanical guidelines given in Sections 3.3.2 and 3.3.3. Ask your Intel sales representative for additional information.

For Intel enabled vendor information for the Intel Pentium 4 processor in the 478-pin package thermal mechanical support components, refer to the following website:

<http://developer.intel.com/design/Pentium4/components/478pin.htm>

## 4 Conclusion

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

The Intel® Pentium® 4 processor in the 478-pin package and the Intel® Pentium® 4 processor with 512 KB L2 cache on .13 micron process have thermal management logic integrated into the processor silicon. Their circuits may be configured to automatically control the processor temperature through the use of the Thermal Monitor feature. In the event it reaches a factory-calibrated temperature, the processor periodically stops the internal clocks in order to reduce power consumption and allow the processor to cool down and stay within thermal specifications. Various registers and bus signals are available to monitor and control the processor thermal status. A chassis cooling solution designed to the thermal design power (TDP) as specified in the processor datasheet document can 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.

The size and type of the heatsink, 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 heatsink solution for a system based on an Intel Pentium 4 processor in the 478-pin package. Properly designed solutions provide adequate cooling to maintain the processor thermal specification. This is accomplished by providing a low local ambient temperature and creating a minimal thermal resistance to that local ambient temperature. Fan heatsinks or ducting can be used to cool the processor if proper package temperatures cannot be maintained otherwise. By maintaining the processor case temperature at the values specified in the processor datasheet, a system designer can be confident of proper functionality and reliability of these processors.



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# Appendix A: Thermal Interface Management

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To optimize the heatsink design for the Intel® Pentium® 4 processor in the 478-pin package, it is important to understand the impact of factors related to the interface between the processor and the heatsink base. Specifically, the bond line thickness, interface material area and interface material thermal conductivity should be managed to realize the most effective thermal solution.

## Bond Line Management

Any gap between the processor integrated heat spreader (IHS) and the heatsink base impacts 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 and roughness of both the heatsink base and the integrated heat spreader, plus the thickness of the thermal interface material (for example thermal grease) used between these two surfaces and the clamping force applied by the heatsink attach clip(s).

## Interface Material Area

The size of the contact area between the processor and the heatsink 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 478-pin package has an IHS surface.

## Interface Material Performance

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

- Thermal resistance of the material
- 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 interface material is at transferring heat. The thermal resistance of the interface material has a significant impact on the thermal performance of the overall thermal solution. The higher the thermal resistance, the larger the temperature drop is across the interface and the more efficient the thermal solution (heatsink, fan) 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 heatsink retention mechanism, to spread and fill the gap between the processor and the heatsink. 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.



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## ***Appendix B: Mechanical Drawings***

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Figure 22 through Figure 26 reference the mechanical enabling components for the Intel® Pentium® 4 processor in the 478-pin package.

**Note:** Shock and vibration validation as well as thermal validation have been completed according to the validation criteria given section 3.1. However, Intel reserves the right to make changes and modifications to the design as necessary.



Figure 22. Retention Mechanism – 1

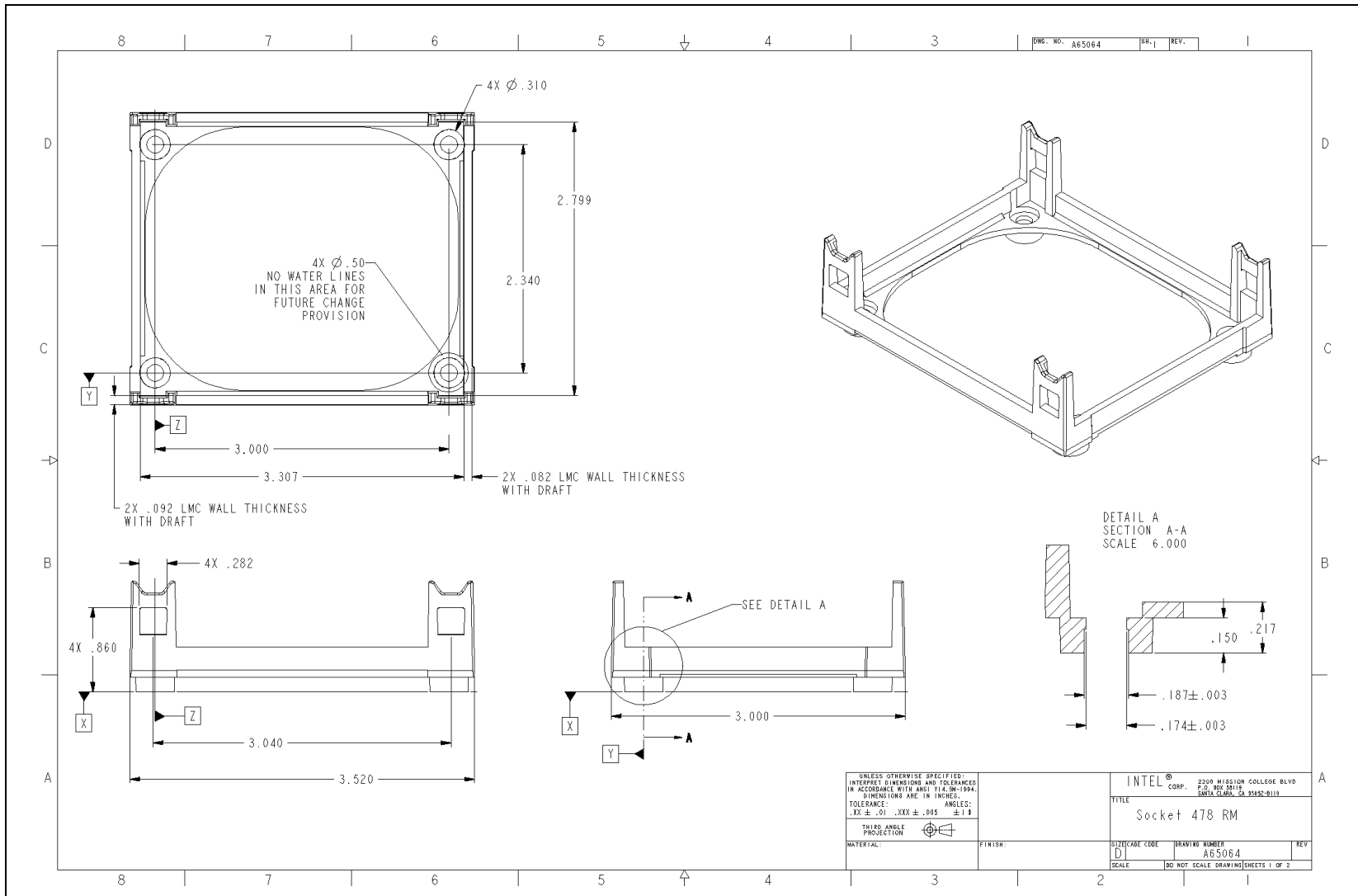






Figure 23. Retention Mechanism – 2

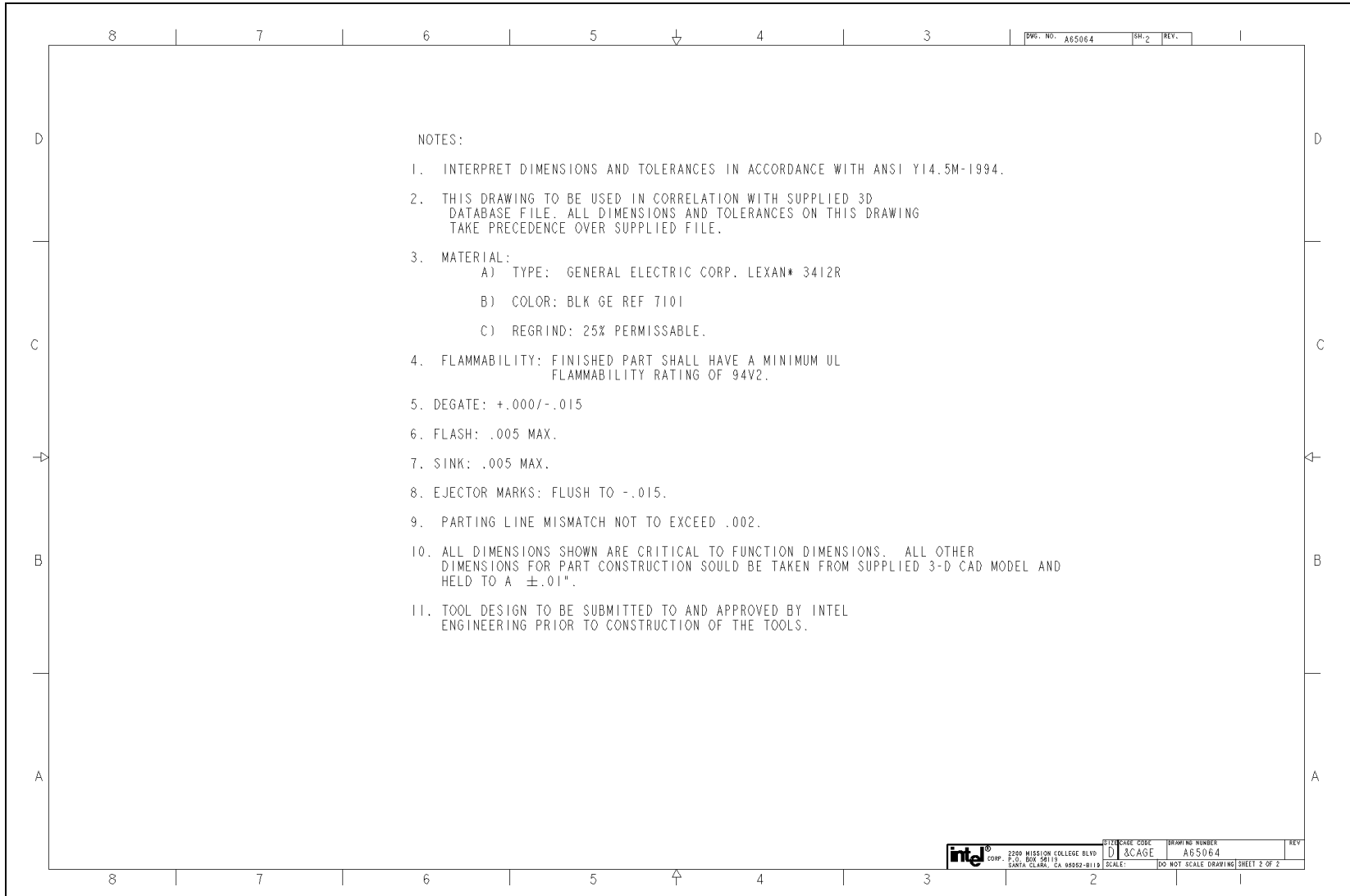




Figure 24. Clip Frame

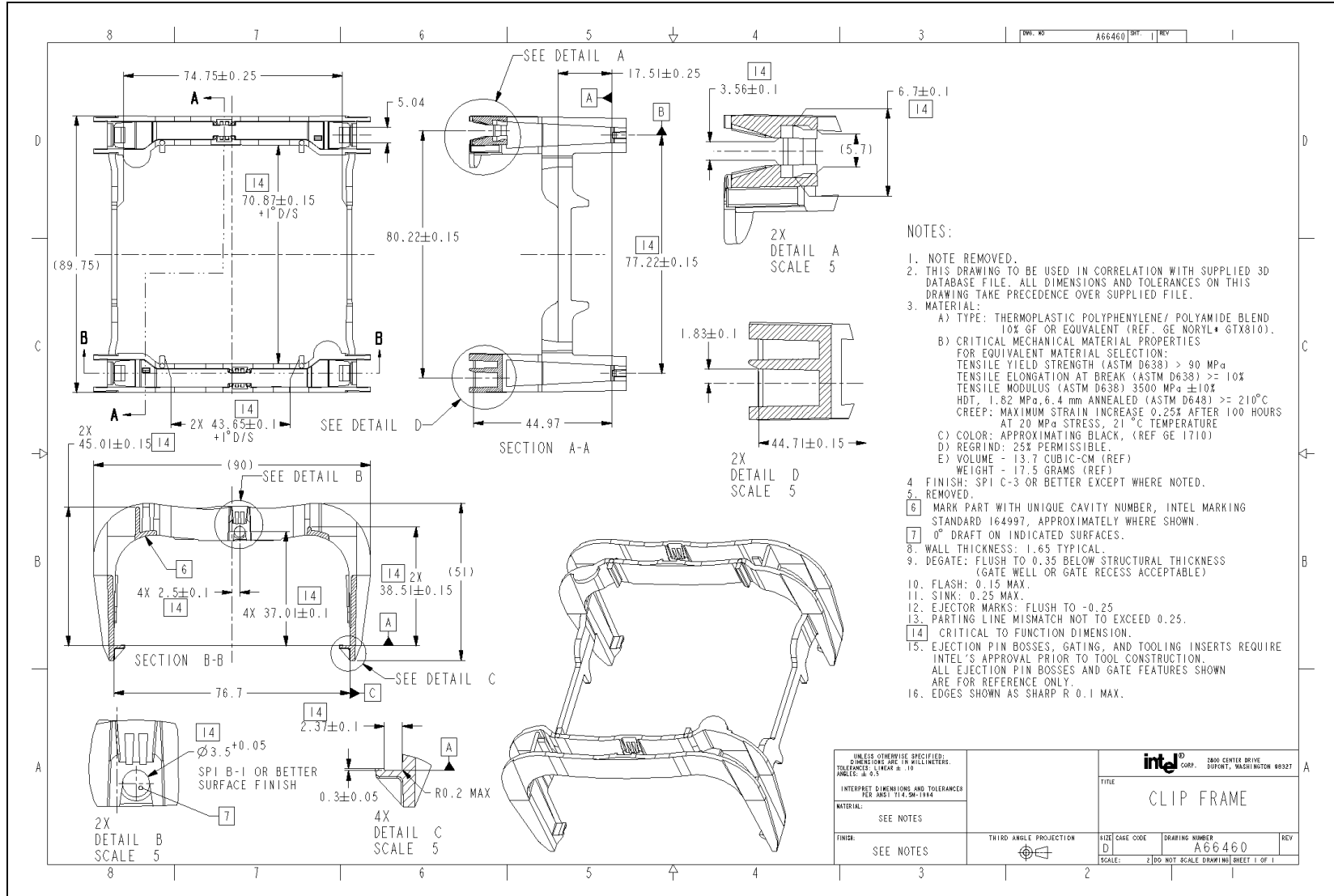


Figure 25. Clip Lever

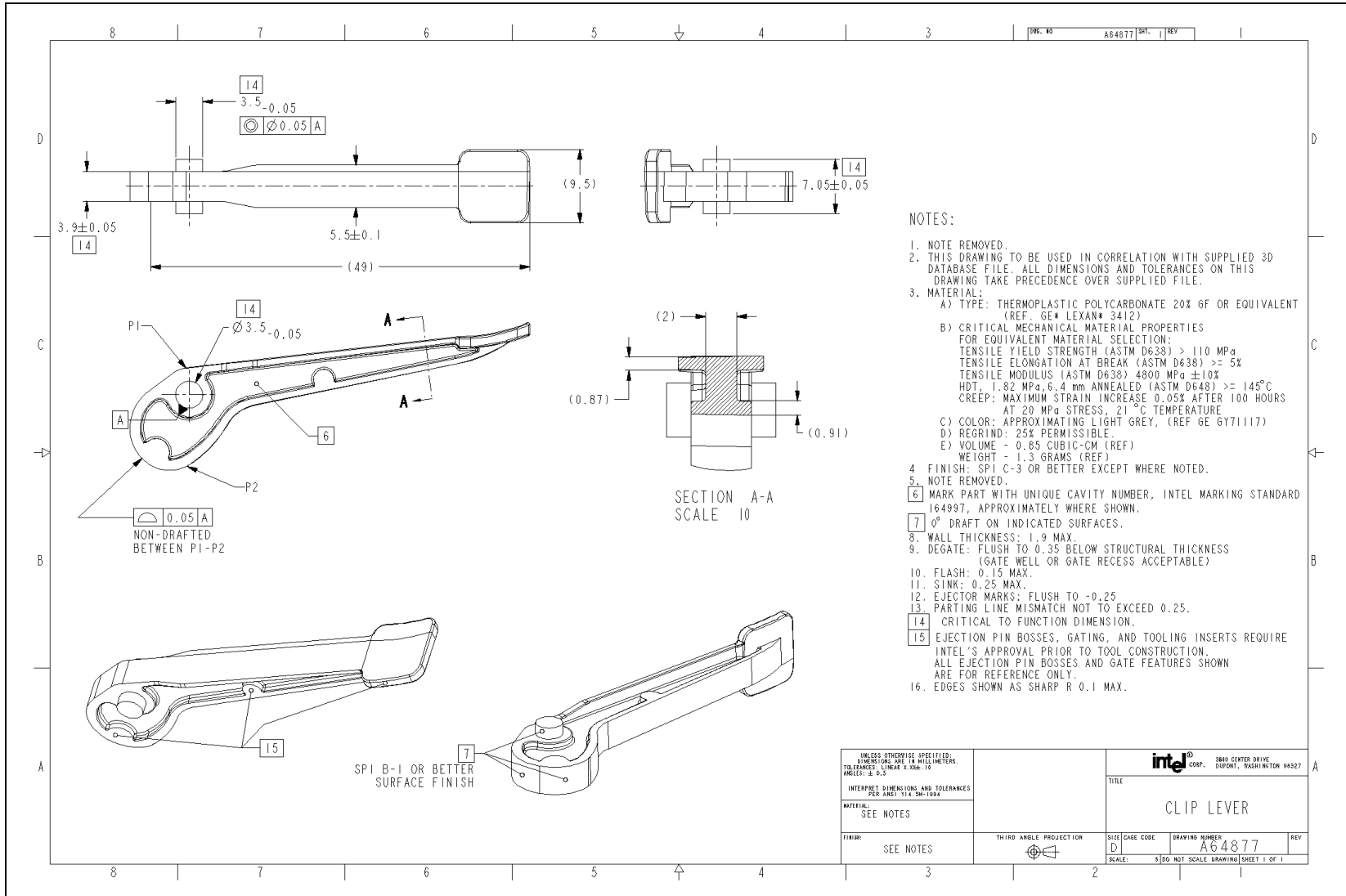




Figure 26. Clip Assembly

