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Intel® Pentium® 4 Processor 651 with Hyper-Threading Technology† for Embedded Applications

Thermal Design Guidelines

February 2006

Rev. 001

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Revision History

Date	Revision	Description
February 2006	1.0	Initial release of this Document

1   Introduction

1.1   Document Goals and Scope

1.1.1   Importance of Thermal Management

The objective of thermal management is to ensure that the temperatures of all components in a system are maintained within their functional temperature range. Within this temperature range, a component 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 to its operating characteristics.

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 in particular on the component power dissipation, the processor package thermal characteristics, and the processor thermal solution.

All of these parameters are affected by the continued push to increase processor performance levels and packaging density (more transistors). As operating frequencies increase and packaging size decreases, the power density increases while the thermal solution space and airflow typically become more constrained or remain the same within the system. The result is the increased importance of system design to ensure that thermal design requirements are met for the processor and other system components.

1.1.2   Document Goals

Depending on the type of system and the chassis characteristics, new system and component designs may be required for 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 using the Intel® Pentium® 4 Processor 651 with Hyper-Threading Technology[†].

The concepts given in this document are applicable to any system form factor. Specific examples used will be the Intel enabled reference solution for 1U/2U systems. Please see the applicable ATX and BTX form factor reference documents and thermal design guidelines to design a thermal solution for those form factors.

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1.1.3 Document Scope

This design guide supports the following processors:

- Intel Pentium 4 Processor 651 with HT Technology

In this document, when a reference is made to "the processor" it is intended that this includes the Intel Pentium 4 Processor 651 with HT Technology unless otherwise specified.

In this document, when a reference is made to the datasheet, the reader should refer to the *Intel® Pentium® 4 Processor 6x1Δ Sequence Datasheet On 65 nm Process in the 775-land LGA Package and supporting Intel® Extended Memory 64 TechnologyΦ*.

- **Section 2** discusses package thermal mechanical requirements to design a thermal solution for the Intel Pentium 4 Processor 651 with HT Technology in the context of embedded computer applications.

- **Section 3** discusses the thermal solution considerations and metrology recommendations to validate a processor thermal solution.

- **Section 4** addresses the benefits of the processor's integrated thermal management logic for thermal design.

- **Section 5** gives information on the Intel reference thermal solution for the processor.

The physical dimensions and thermal specifications of the processor used in this document are for illustration only. Refer to the Datasheet for the product dimensions, thermal power dissipation, and maximum case temperature. In case of conflict, the data in the Datasheet supersedes any data in this document.

1.2 References

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

Document	Comment
Intel® Pentium® 4 Processor 6x1Δ Sequence Datasheet On 65 nm Process in the 775-land LGA Package and supporting Intel® Extended Memory 64 TechnologyΦ	See Note 1.
Thermal Readiness for Performance FMB Platforms User's Guide	See Note 1.
LGA775 Socket Mechanical Design Guide	See Note 1.
Thermocouple Attach Using Solder – Video CD-ROM	See Note 1.
Manufacturing with Intel® Components using 775-Land LGA Package and LGA775 Socket - System Assembly	Available electronically
Fan Specification for 4-wire PWM Controlled Fans	http://www.formfactors.org/
Intel® Pentium® 4 Processor on 90nm Process in the 775-Land LGA Package Reference Heat Sink Attach Mechanism Information	Available electronically
2005 Processors in the 775-Land LGA Package, Thermal Test Kit Information	Available Electronically
Performance ATX Desktop System Thermal Design Suggestions	http://www.formfactors.org/
Performance microATX Desktop System Thermal Design Suggestions	http://www.formfactors.org/
Balanced Technology Extended (BTX) System Design Guide	http://www.formfactors.org/
Thin Electronics Bay (1U/2U) Specifications	http://www.ssiforum.org/default.aspx

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1. Contact your Intel field sales representative for the latest revision and order number of this document.

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1.3 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 heat sink or at the fan inlet for an active heat sink. Also referred to as T_{LA}.
T_C	The case temperature of the processor, measured at the geometric center of the topside of the IHS.
T_E	The ambient air temperature external to a system chassis. This temperature is usually measured at the chassis air inlets. Also referred to as T_{EXT}.
T_S	Heat sink temperature measured on the underside of the heat sink base, at a location corresponding to T_C.
T_{C-MAX}	The maximum case temperature as specified in a component specification.
Ψ_{CA}	Case-to-ambient thermal characterization parameter (psi). A measure of thermal solution performance using total package power. Defined as $(T_C - T_A)$ / Total Package Power. Note: Heat source must be specified for Ψ measurements.
Ψ_{CS}	Case-to-sink thermal characterization parameter. A measure of thermal interface material performance using total package power. Defined as $(T_C - T_S)$ / Total Package Power. Also referred to as Ψ_{TIM}. Note: Heat source must be specified for Ψ measurements.
Ψ_{SA}	Sink-to-ambient thermal characterization parameter. A measure of heat sink thermal performance using total package power. Defined as $(T_S - T_A)$ / Total Package Power. Note: Heat source must be specified for Ψ measurements.
TIM	Thermal Interface Material: The thermally conductive compound between the heat sink and the processor case. This material fills the air gaps and voids, and enhances the transfer of the heat from the processor case to the heat sink.
P_{MAX}	The maximum power dissipated by a semiconductor component.
TDP	Thermal Design Power: a power dissipation target based on worst-case applications. Thermal solutions should be designed to dissipate the thermal design power.
IHS	Integrated Heat Spreader: a thermally conductive lid integrated into a processor package to improve heat transfer to a thermal solution through heat spreading.
LGA775 Socket	The surface mount socket designed to accept the processors in the 775-Land LGA package.
ACPI	Advanced Configuration and Power Interface.
Bypass	The area between a passive heat sink and any object that can act to form a duct. For this example, it can be expressed as the space from the outside of the fins to the nearest surface.
FMB	Flexible Motherboard Guideline: an estimate of the maximum value of a processor specification over certain time periods. System designers should meet the FMB values to ensure their systems are compatible with future processor releases. This design guide covers the requirements for the 2005 Performance Universal FMB and the 2005 Mainstream / Value FMB.
Thermal Monitor	A feature on the processor that attempts to keep the processor die temperature within factory specifications.

Term	Description
TCC	Thermal Control Circuit: the Thermal Monitor uses the TCC to reduce die temperature by lowering effective processor frequency when the die temperature has exceeded its operating limits.
T_{DIODE}	Temperature reported from the on-die thermal diode.
FSC	Fan Speed Control: Thermal solution that includes a variable fan speed which is driven by a PWM signal and uses the on-die thermal diode as a reference to change the duty cycle of the PWM signal.
$T_{CONTROL\_BASE}$	Constant from the processor Datasheet that is added to the $T_{CONTROL\_OFFSET}$ that results in the value for $T_{CONTROL}$.
$T_{CONTROL\_OFFSET}$	Value read by the BIOS from a processor MSR and added to the $T_{CONTROL\_BASE}$ that results in the value for $T_{CONTROL}$.
$T_{CONTROL}$	The specification limit for use with the on-die thermal diode.
PWM	Pulse Width Modulation: a method of controlling a variable speed fan. The enabled 4 wire fans use the PWM duty cycle % from the fan speed controller to modulate the fan speed.
Health Monitor Component	Any stand-alone or integrated component that is capable of reading the processor temperature and providing the PWM signal to the 4 pin fan header.
VR	Voltage regulator.
CFM	Volumetric air flow rate in cubic feet per minute.
P_D	Processor total power dissipation (W) (assumes all power dissipates through the IHS).
1U, 2U	Form Factors: 1U = 1.75 in. and 2U = 3.5 in.

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2 Processor Thermal/Mechanical Information

2.1 Mechanical Requirements

2.1.1 Processor Package

The processors covered in this document are packaged in a 775-Land LGA package that interfaces with the motherboard via a LGA775 socket. Please refer to the Datasheet for detailed mechanical specifications.

The processor connects to the motherboard through a Land Grid Array (LGA) surface mount socket. The socket contains 775 contacts arrayed about a cavity in the center of the socket with solder balls for surface mounting to the motherboard. The socket is named LGA775 socket. A description of the socket can be found in the *LGA775 Socket Mechanical Design Guide*.

The package includes an integrated heat spreader (IHS), shown in Figure 1 for illustration only. Refer to the processor Datasheet for further information. In case of conflict, package dimensions in the processor Datasheet supersede dimensions provided in this document.

Figure 1. Package IHS Load Areas
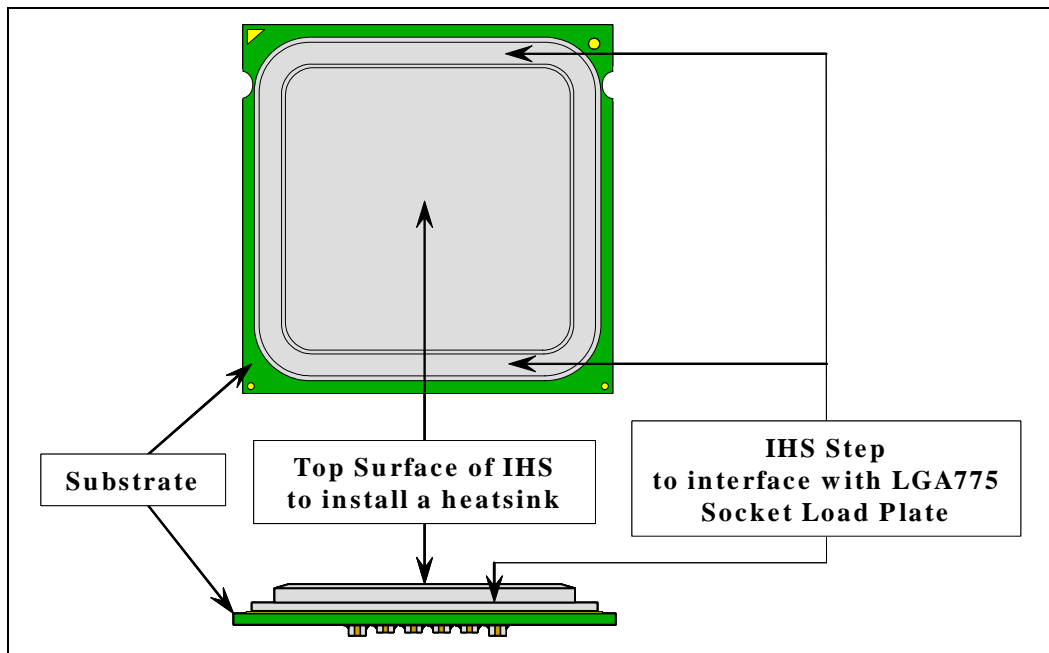
The primary function of the IHS is to transfer the non-uniform heat distribution from the die to the top of the IHS, out of which the heat flux is more uniform and spread over a larger surface area (not the entire IHS area). This allows more efficient heat transfer out of the package to an attached cooling device. The top surface of the IHS is designed to be the interface for contacting a heat sink.

The IHS also features a step that interfaces with the LGA775 socket load plate, as described in the *LGA775 Socket Mechanical Design Guide*. The load from the load plate is distributed across two sides of the package onto a step on each side of the IHS. It is then distributed by the package across all of the contacts. When correctly actuated, the top surface of the IHS is above the load plate, allowing proper installation of a heat sink on the top surface of the IHS. After actuation of the socket load plate, the seating plane of the package is flush with the seating plane of the socket. Package movement during socket actuation is along the Z-direction (perpendicular to substrate) only. Refer to the *LGA775 Socket Mechanical Design Guide* for further information about the LGA775 socket.

The processor package has mechanical load limits that are specified in the processor Datasheet. The specified maximum static and dynamic load limits should not be exceeded during their respective stress conditions. These include heat sink installation, removal, mechanical stress testing, and standard shipping conditions.

- When a compressive static load is necessary to ensure thermal performance of the thermal interface material between the heat sink base and the IHS, it should not exceed the corresponding specification given in the processor Datasheet.

- When a compressive static load is necessary to ensure mechanical performance, it should remain in the minimum/maximum range specified in the processor Datasheet.

- The heat sink mass can also generate additional dynamic compressive load to the package during a mechanical shock event. Amplification factors due to the impact force during shock must be taken into account in dynamic load calculations. The total combination of dynamic and static compressive load should not exceed the processor Datasheet compressive dynamic load specification during a vertical shock. For example, with a 0.454 kg [1 lb] heat sink, an acceleration of 50G during an 11 ms trapezoidal shock with an amplification factor of 2 results in approximately a 445 N [100 lbf] dynamic load on the processor package. If a 178 N [40 lbf] static load is also applied on the heat sink for thermal performance of the thermal interface material, the processor package could see up to a 623 N [140 lbf]. The calculation for the thermal solution of interest should be compared to the processor Datasheet specification.

No portion of the substrate should be used as a load-bearing surface.

Finally, the processor Datasheet provides package handling guidelines in terms of maximum recommended shear, tensile, and torque loads for the processor IHS relative to a fixed substrate. These recommendations should be followed in particular for heat sink removal operations.

2.1.2   Heat Sink Attach

2.1.2.1   General Guidelines

There are no features on the LGA775 socket to directly attach a heat sink: a mechanism must be designed to attach the heat sink directly to the motherboard. In addition to holding the heat sink

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in 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 (TIM) applied between the IHS and the heat sink. TIMs based on phase change materials are very sensitive to applied pressure: the higher the pressure, the better the initial performance. TIMs such as thermal greases are not as sensitive to applied pressure. Designs should consider a possible decrease in applied pressure over time due to potential structural relaxation in retention components.

- Ensuring system electrical, thermal, and structural integrity under shock and vibration events. The mechanical requirements of the heat sink attach mechanism depend on the mass of the heat sink and the level of shock and vibration that the system must support. The overall structural design of the motherboard and the system have to be considered when designing the heat sink attach mechanism. Their design should provide a means for protecting LGA775 socket solder joints. One of the strategies for mechanical protection of the socket is to use a preload and high stiffness clip. Information on how this strategy is implemented can be seen in the *Intel*® *Pentium*® *4 Processor 651 with Hyper-Threading Technology[†] Thermal Design Guidelines*.

Note: Package pull-out during mechanical shock and vibration is constrained by the LGA775 socket load plate (refer to the *LGA775 Socket Mechanical Design Guide* for further information).

2.1.2.2 Heat Sink Clip Load Requirement

The attach mechanism for the heat sink developed to support the processor should create a static preload on the package between **18 lbf** and **70 lbf** throughout the life of the product for designs compliant with the Intel reference design assumption:

- 72 mm x 72 mm mounting hole span (refer to Figure 43)

The minimum load is required to protect against fatigue failure of the socket solder joint in temperature cycling.

It is important to take into account potential load degradation from creep over time when designing the clip and fastener to the required minimum load. This means that, depending on clip stiffness, the initial preload at beginning of life of the product may be significantly higher than the minimum preload that must be met throughout the life of the product. For additional guidelines on mechanical design, in particular on designs departing from the reference design assumptions refer to Appendix A:.

For information on clip loading, see the *Intel*® *Pentium*® *D Processor, Intel*® *Pentium*® *Processor Extreme Edition and Intel*® *Pentium*® *4 Processor Thermal and Mechanical Design Guidelines (TMDG) For the Intel*® *Pentium*® *D Processor 800*[Δ] *and 900*[Δ] *Sequences, Intel*® *Pentium*® *Processor Extreme Edition 840*[Δ] *and 955*[Δ] *and Intel*® *Pentium*® *4 Processor 6x1*[Δ] *Sequence*.

2.1.2.3 Additional Guidelines

In addition to the general guidelines given above, the heat sink attachment mechanism for the processor should be designed to the following guidelines:

- *Holds the heat sink in place under mechanical shock and vibration events and applies force to the heat sink base to maintain desired pressure on the thermal interface material.* Note that the load applied by the heat sink attach mechanism must comply with the package specifications described in the processor Datasheet. One of the key design parameters is the

height of the top surface of the processor IHS above the motherboard. The IHS height from the top of board is expected to vary from 7.517 mm to 8.167 mm. This data is provided for information only, and should be derived from:

— The height of the socket seating plane above the motherboard after reflow, given in the *LGA775 Socket Mechanical Design Guide* with its tolerances.

— The height of the package, from the package seating plane to the top of the IHS, and accounting for its nominal variation and tolerances that are given in the corresponding processor Datasheet.

- *Engages easily, and if possible, without the use of special tools*. In general, the heat sink is assumed to be installed after the motherboard has been installed in the chassis.

- *Minimizes contact with the motherboard surface during installation* and actuation to avoid scratching the motherboard.

2.2　Thermal Requirements

Refer to the Datasheet for the processor thermal specifications. The majority of processor power is dissipated through the IHS. There are no additional components, e.g., BSRAMs, which generate heat on this package. The amount of power that can be dissipated as heat through the processor package substrate and into the socket is usually minimal.

The thermal limits for the processor are the Thermal Profile and $T_{CONTROL}$. The Thermal Profile defines the maximum case temperature as a function of power being dissipated. $T_{CONTROL}$ is a specification used in conjunction with the temperature reported by the on-die thermal diode and a fan speed control method. Designing to these specifications allows optimization of thermal designs for processor performance and acoustic noise reduction.

2.2.1　Processor Case Temperature

For the processor, the case temperature is defined as the temperature measured at the geometric center of the package on the surface of the IHS. Figure 2 illustrates the measurement location for a 37.5 mm x 37.5 mm [1.474 in x 1.474 in] 775-Land LGA processor package with a 28.7 mm x 28.7 mm [1.13 in x 1.13 in] IHS top surface. Techniques for measuring the case temperature are detailed in Section 3.4.

Note: In case of conflict, the package dimensions in the processor Datasheet supersede dimensions provided in this document.

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Figure 2. Processor Case Temperature Measurement Location

Measure T_C at this point
(geometric center of the package)

37.5 mm

37.5 mm
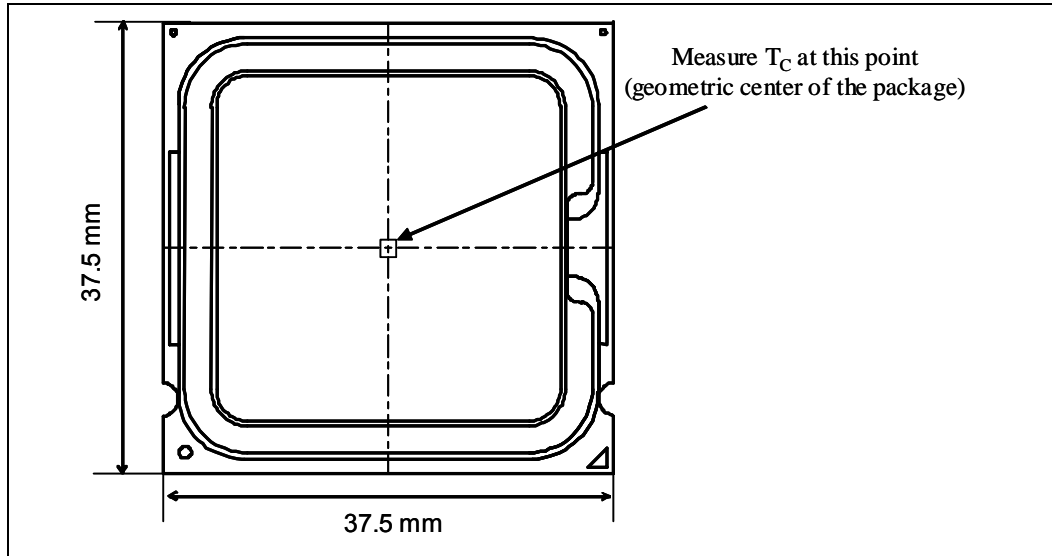
2.2.2 Thermal Profile

The Thermal Profile defines the maximum case temperature as a function of processor power dissipation. The TDP and Maximum Case Temperature are defined as the maximum values of the thermal profile. By design the thermal solutions must meet the thermal profile for all system operating conditions and processor power levels.

The slope of the thermal profile was established assuming a generational improvement in thermal solution performance of about 10 percent over the previous Intel reference design. This performance is expressed as the slope on the thermal profile and can be thought of as the thermal resistance of the heat sink attached to the processor, Ψ_{CA} (Refer to section 3.1). The intercept on the thermal profile assumes a maximum ambient operating condition that is consistent with the available chassis solutions.

To determine compliance to the thermal profile, a measurement of the actual processor power dissipation is required. The measured power is plotted on the Thermal Profile to determine the maximum case temperature. Using the example in Figure 3 for a processor dissipating 70 W the maximum case temperature is 61° C. See the Datasheet for the thermal profile. See the *Thermal Readiness for Performance FMB Platforms User's Guide* for specific details on power measurement.

Figure 3. Example Thermal Profile
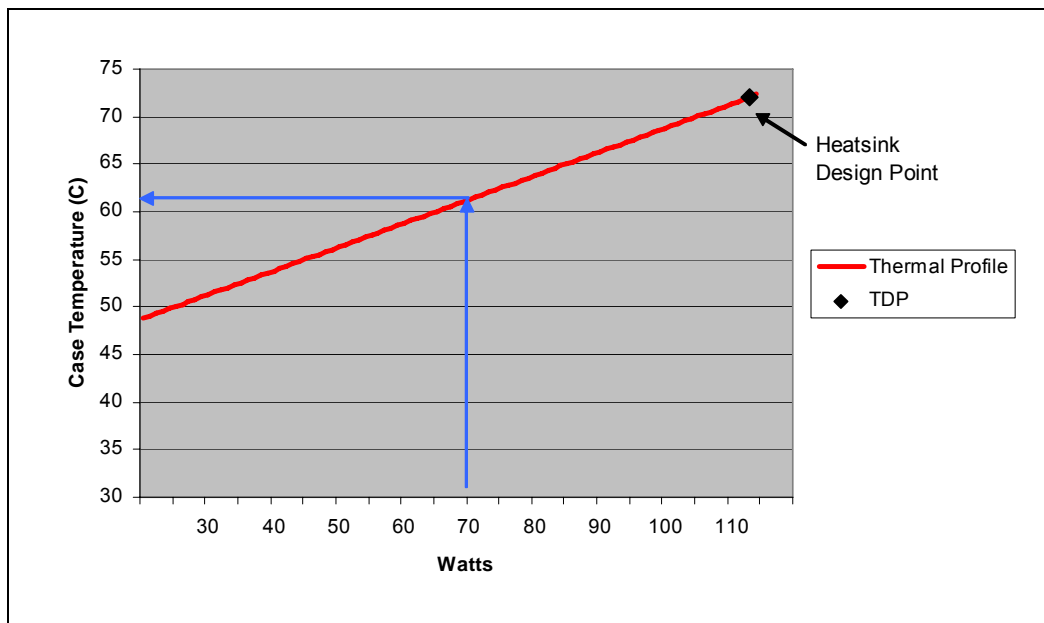
2.2.3 T$_{CONTROL}$

T$_{CONTROL}$ defines the maximum operating temperature for the on-die thermal diode when the thermal solution fan speed is being controlled by the on-die thermal diode. The T$_{CONTROL}$ parameter defines a very specific processor operating region where fan speed can be reduced. This allows the system integrator a method to reduce the acoustic noise of the processor cooling solution, while maintaining compliance to the processor thermal specification.

The value of T$_{CONTROL}$ is driven by a number of factors. One of the most significant of these is the processor idle power. As a result, a processor with a high T$_{CONTROL}$ will dissipate more power than a part with lower value of T$_{CONTROL}$ when running the same application.

The value of T$_{CONTROL}$ is calculated such that regardless of the individual processor's T$_{CONTROL}$ value the thermal solution should perform similarly. The higher power of some parts is offset by a higher value of T$_{CONTROL}$ in such a way that they should behave virtually the same acoustically

This is achieved in part by using the Ψ_{CA} vs. RPM and RPM vs. Acoustics (dBA) performance curves from the Intel enabled thermal solution. A thermal solution designed to meet the thermal profile should have similar acoustic performance for any value of T$_{CONTROL}$.

See the *Intel*® *Pentium*® *D Processor, Intel*® *Pentium*® *Processor Extreme Edition and Intel*® *Pentium*® *4 Processor Thermal and Mechanical Design Guidelines (TMDG) For the Intel*® *Pentium*® *D Processor 800*$^\Delta$ *and 900*$^\Delta$ *Sequences, Intel*® *Pentium*® *Processor Extreme Edition 840*$^\Delta$ *and 955*$^\Delta$ *and Intel*® *Pentium*® *4 Processor 6x1*$^\Delta$ *Sequence* for details on implementing a design using T$_{CONTROL}$ and the thermal profile.

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2.3 Heat Sink Design Considerations

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

- **The area of the surface on which the heat transfer takes place**. Without any enhancements, this is the surface of the processor package IHS. One method used to improve thermal performance is by attaching a heat sink to the IHS. A heat sink can increase the effective heat transfer surface area by conducting heat out of the IHS and into the surrounding air through fins attached to the heat sink base.

- **The conduction path from the heat source to the heat sink fins**. Providing a direct conduction path from the heat source to the heat sink fins and selecting materials with higher thermal conductivity typically improves heat sink performance. The length, thickness, and conductivity of the conduction path from the heat source to the fins directly impact the thermal performance of the heat sink. In particular, the quality of the contact between the package IHS and the heat sink base has a higher impact on the overall thermal solution performance as processor cooling requirements become stricter. Thermal interface material (TIM) is used to fill in the gap between the IHS and the bottom surface of the heat sink, and thereby improve the overall performance of the stack-up (IHS-TIM-Heat sink). With extremely poor heat sink 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 applied to it. Refer to Section 2.3.4 below and Appendix B: for further information on TIM and bond line management between the IHS and the heat sink 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, T_A, and the local air velocity over the surface. The higher the air velocity over the surface, and the cooler the air, the more efficient is the resulting cooling. The nature of the airflow can also enhance heat transfer via convection. Turbulent flow can provide improvement over laminar flow. In the case of a heat sink, the surface exposed to the flow includes in particular the fin faces and the heat sink base.

Active heat sinks typically incorporate a fan that helps manage the airflow through the heat sink.

Passive heat sink solutions require in-depth knowledge of the airflow in the chassis. Typically, passive heat sinks see lower air speed. These heat sinks are therefore typically larger (and heavier) than active heat sinks due to the increase in fin surface required to meet a required performance specification. As the heat sink 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 heat sink instead of through it, unless air bypass is carefully managed. Using air-ducting techniques to manage bypass area can be an effective method for controlling airflow through the heat sink.

2.3.1 Heat Sink Size

The size of the heat sink is dictated by height restrictions for installation in a system, by the real estate available on the motherboard, and other considerations for component height and placement in the area potentially impacted by the processor heat sink. The height of the heat sink must comply with the requirements and recommendations published for the motherboard form factor of interest. Designing a heat sink to the recommendations may preclude using it in system adhering strictly to the form factor requirements, while still in compliance with the form factor documentation.

For the 1U/2U form factor, it is recommended to use:

- The 1U/2U motherboard keep-out footprint definition and height restrictions for enabling components, defined for the platforms designed with the LGA775 socket in Appendix E: of this design guide.

- The motherboard primary side height constraints defined in the *Thin Electronics Bay* specification located at http://www.ssiforum.org/.

The resulting space available above the motherboard is generally not entirely available for the heat sink. The target height of the heat sink must take into account airflow considerations (for fan performance for example) as well as other design considerations (air duct, etc.).

2.3.2 Heat Sink Mass

With the need to push air cooling to better performance, heat sink solutions tend to grow larger (increase in fin surface) resulting in increased mass. The insertion of highly thermally conductive materials like copper to increase heat sink thermal conduction performance results in even heavier solutions. As mentioned in Section 2.1, the heat sink mass must take into consideration the package and socket load limits, the heat sink attach mechanical capabilities, and the mechanical shock and vibration profile targets. Beyond a certain heat sink mass, the cost of developing and implementing a heat sink attach mechanism that can ensure the system integrity under the mechanical shock and vibration profile targets may become prohibitive.

2.3.3 Package IHS Flatness

The package IHS flatness for the product is specified in the Datasheet and can be used as a baseline to predict heat sink performance during the design phase.

Intel recommends testing and validating heat sink performance in full mechanical enabling configuration to capture any impact of IHS flatness change due to combined socket and heat sink loading. While socket loading alone may increase the IHS warpage, the heat sink preload redistributes the load on the package and improves the resulting IHS flatness in the enabled state.

2.3.4 Thermal Interface Material

Thermal interface material application between the processor IHS and the heat sink base is required to improve thermal conduction from the IHS to the heat sink. Many thermal interface materials can be pre-applied to the heat sink base prior to shipment from the heat sink supplier and allow direct heat sink 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 heat sink base in a way that ensures the entire processor IHS area is covered. It is important to compensate for heat sink-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 heat sink installation.

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2.4 System Thermal Solution Considerations

2.4.1 Chassis Thermal Design Capabilities

The Intel reference thermal solution for a 1U chassis assumes that the chassis delivers a maximum T_A of 38–40° C with 15–25 CFM of airflow at the inlet of the processor heat sink. The Intel reference thermal solution for a 2U chassis assumes that the chassis delivers a maximum T_A of 38–44° C with 15–35 CFM of airflow at the inlet of the processor heat sink (refer to Section 5).

2.4.2 Improving Chassis Thermal Performance

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 determine the chassis thermal performance, and the resulting ambient temperature around the processor. The size and type (passive or active) of the thermal solution and the amount of system airflow can be traded off against each other to meet specific system design constraints. Additional constraints are board layout, spacing, component placement, acoustic requirements, and structural considerations that limit the thermal solution size. For more information, refer to the Thin Electronics Bay specification at the following web site: www.ssiforum.org.

In addition to passive heat sinks, fan heat sinks and system fans are other solutions that 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 thermal solutions, the Thermal Monitor feature and associated logic have been integrated into the silicon of the processor. By taking advantage of the Thermal Monitor feature, system designers may reduce thermal solution cost by designing to TDP instead of maximum power. Thermal Monitor attempts to protect the processor during sustained workload above TDP. Implementation options and recommendations are described in Section 4.

2.4.3 Summary

In summary, considerations in heat sink design include:

- The local ambient temperature T_A at the heat sink, which is a function of chassis design.

- The thermal design power (TDP) of the processor, and the corresponding maximum T_C as calculated from the thermal profile. These parameters are usually combined in a single lump cooling performance parameter, Ψ_{CA} (case to air thermal characterization parameter). More information on the definition and the use of Ψ_{CA} is given Section 3.1.

- Heat sink interface to IHS surface characteristics, including flatness and roughness.

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- The performance of the thermal interface material used between the heat sink and the IHS.

- The required heat sink clip static load, between 18 lbf to 70 lbf throughout the life of the product (refer to Section 2.1.2.2 for further information).

- Surface area of the heat sink.

- Heat sink material and technology.

- Volume of airflow over the heat sink surface area.

- Development of airflow entering and within the heat sink area.

- Physical volumetric constraints placed by the system

2.5　System Integration Considerations

Manufacturing with Intel® Components using 775-Land LGA Package and LGA775 Socket documentation provides Best Known Methods for all aspects of LGA775 socket-based platforms and systems manufacturing. Of particular interest for package and heat sink installation and removal is the *System Assembly* section. A video covering system integration is also available. Contact your Intel field representative for further information.

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3 Thermal Metrology

This section discusses guidelines for testing thermal solutions, including measuring processor temperatures. In all cases, the thermal engineer must measure power dissipation and temperature to validate a thermal solution. To define the performance of a thermal solution, the "thermal characterization parameter" Ψ ("psi") will be used.

3.1 Characterizing Cooling Performance Requirements

The idea of a "thermal characterization parameter", Ψ ("psi"), is a convenient way to characterize the performance needed for the thermal solution and to compare thermal solutions in identical situations (same heat source and local ambient conditions). The thermal characterization parameter is calculated using total package power.

Note: Heat transfer is a three-dimensional phenomenon that can rarely be accurately and easily modeled by a single resistance parameter like Ψ.

The case-to-local ambient thermal characterization parameter value (Ψ_{CA}) is used as a measure of the thermal performance of the overall thermal solution that is attached to the processor package. It is defined by Equation 1 below, and measured in units of °C/W:

Equation 1: Case-to-Ambient Thermal Characterization

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

Where:

Ψ_{CA} = Case-to-local ambient thermal characterization parameter (°C/W)

T_C = Processor case temperature (°C)

T_A = Local ambient temperature in chassis at processor (°C)

P_D = Processor total power dissipation (W) (assumes all power dissipates through the IHS). It can be replaced by Thermal Design Power (TDP).

The case-to-local ambient thermal characterization parameter of the processor, Ψ_{CA}, is comprised of Ψ_{CS}, the thermal interface material thermal characterization parameter, and of Ψ_{SA}, the sink-to-local ambient thermal characterization parameter, as shown in the equation below:

$$\Psi_{CA} = \Psi_{CS} + \Psi_{SA}$$

Where:

Ψ_{CS} = Thermal characterization parameter of the thermal interface material (°C/W)

Ψ_{SA} = Thermal characterization parameter from heat sink-to-local ambient (°C/W)

Ψ_{CS} is strongly dependent on the thermal conductivity and thickness of the TIM between the heat sink and IHS.

Ψ_{SA} is a measure of the thermal characterization parameter from the bottom of the heat sink to the local ambient air. Ψ_{SA} is dependent on the heat sink material, thermal conductivity, and geometry. It is also strongly dependent on the air velocity through the fins of the heat sink.

Figure 4 illustrates the combination of the different thermal characterization parameters.

Figure 4. Processor Thermal Characterization Parameter Relationships
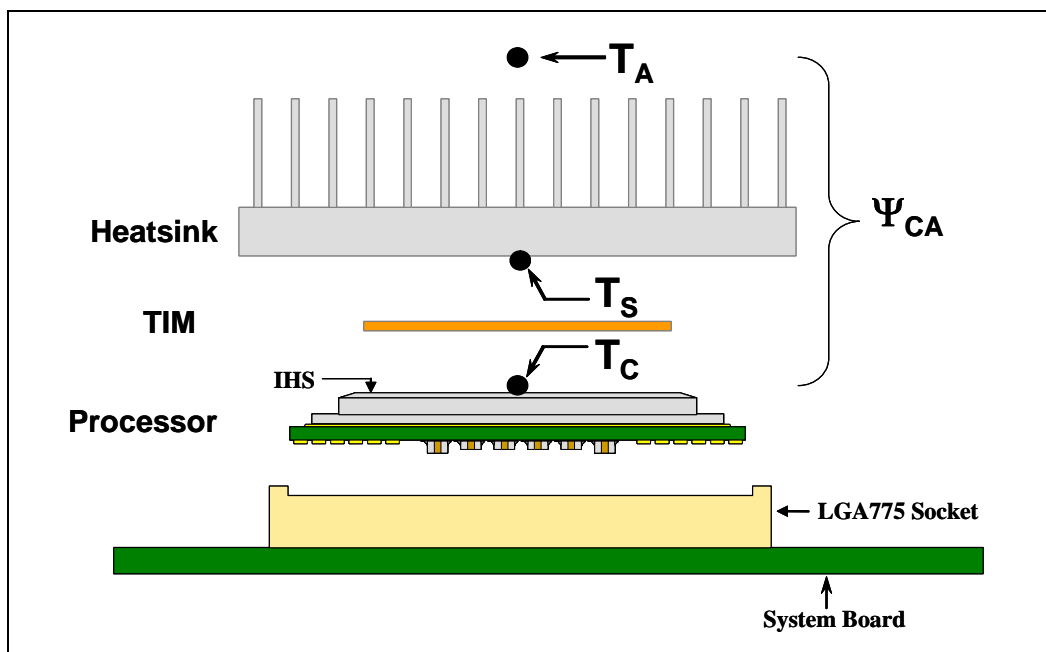
3.1.1   Example

The cooling performance Ψ_{CA} is then defined using the principle of thermal characterization parameter described above:

- The case temperature T_{C-MAX} and thermal design power TDP given in the processor Datasheet.

- Define a target local ambient temperature at the processor, T_A.

Since the processor thermal profile applies to all processor frequencies, it is important to identify the worst case (lowest Ψ_{CA}) for a targeted chassis characterized by T_A to establish a design strategy.

The following provides an illustration of how one might determine the appropriate performance targets. The example power and temperature numbers used here are not related to any specific Intel processor thermal specifications, and are for illustrative purposes only.

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Assume the TDP, as listed in the Datasheet, is 100W and the maximum case temperature from the thermal profile for 100W is 67° C. Assume as well that the system airflow has been designed such that the local ambient temperature is 38° C. Then the following could be calculated using Equation 1 from above:

$$\Psi_{CA} = (T_{C,} - T_A) \text{ / TDP} = (67 - 38) \text{ / } 100 = 0.29 \text{ °C/W}$$

To determine the required heat sink performance, a heat sink solution provider would need to determine Ψ_{CS} performance for the selected TIM and mechanical load configuration. If the heat sink solution were designed to work with a TIM material performing at $\Psi_{CS} \leq 0.10$ °C/W, solving for Equation 2 from above, the performance of the heat sink would be:

$$\Psi_{SA} = \Psi_{CA} - \Psi_{CS} = 0.29 - 0.10 = 0.19 \text{ °C/W}$$

3.2   Processor Thermal Solution Performance Assessment

Thermal performance of a heat sink should be assessed using a thermal test vehicle (TTV) provided by Intel (contact your Intel representative for more information on the Thermal Test Vehicle). The TTV is a stable heat source that the user can make accurate power measurements, whereas processors can introduce additional factors that can impact test results. In particular, the power level from actual processors varies significantly, even when running the maximum power application provided by Intel, due to variances in the manufacturing process. The TTV provides consistent power and power density for thermal solution characterization and results can be easily translated to real processor performance. Accurate measurement of the power dissipated by an actual processor is beyond the scope of this document. See the *Thermal Readiness for Performance FMB Platforms User's Guide* for further information.

Once the thermal solution is designed and validated with the TTV, it is strongly recommended to verify functionality of the thermal solution on real processors and on fully integrated systems (see Appendix D:). The Intel maximum power application enables steady power dissipation on a processor to assist in this testing. Contact your Intel Field Sales representative for a copy of the latest release of the application intended for the Intel® Pentium® 4 Processor 651 with Hyper-Threading Technology[†] for Embedded Applications.

3.3   Local Ambient Temperature Measurement Guidelines

The local ambient temperature T_A is the temperature of the ambient air surrounding the processor. For a passive heat sink, T_A is defined as the air temperature approaching the heat sink; for an actively cooled heat sink, 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 heat sink inlet airflow. This method helps reduce error and eliminate minor spatial variations in

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temperature. The following guidelines are meant to enable accurate determination of the localized air temperature around the processor during system thermal testing.

For **active heat sinks**, it is important to avoid taking measurement in the dead flow zone that usually develops above the fan hub and hub spokes. 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 3 to 8 mm [0.1 to 0.3 in.] above the fan hub vertically and halfway between the fan hub and the fan housing horizontally as shown in Figure 5 (avoiding the hub spokes). Using an open bench to characterize an active heat sink can be useful, and usually ensures more uniform temperatures at the fan inlet. However, additional tests that include a solid barrier above the test motherboard surface can help evaluate the potential impact of the chassis. This barrier is typically clear Plexiglas*, extending at least 100 mm [4 in.] in all directions beyond the edge of the thermal solution. Typical distance from the motherboard to the barrier is 81 mm [3.2 in.]. For even more realistic airflow, the motherboard should be populated with significant elements like memory cards, graphic card, and chipset heat sink. 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, halfway 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 in a chassis with a live motherboard, add-in cards, and other system components, it is likely that the T_A measurements will reveal a highly non-uniform temperature distribution across the inlet fan section.

For **passive heat sinks**, thermocouples should be placed approximately 13 to 25 mm [0.5 to 1.0 in.] away from processor and heat sink as shown in Figure 6. The thermocouples should be placed approximately 51 mm [2.0 in.] above the baseboard. This placement guideline is meant to minimize the effect of localized hot spots from baseboard components.

Note: Testing an active heat sink with a variable speed fan can be done in a thermal chamber to capture the worst-case thermal environment scenarios. Otherwise, when doing a bench top test at room temperature, the fan regulation prevents the heat sink from operating at its maximum capability. To characterize the heat sink capability in the worst-case environment in these conditions, it is then necessary to disable the fan regulation and power the fan directly, based on guidance from the fan supplier.

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Figure 5. Locations for Measuring Local Ambient Temperature, Active Heat Sink
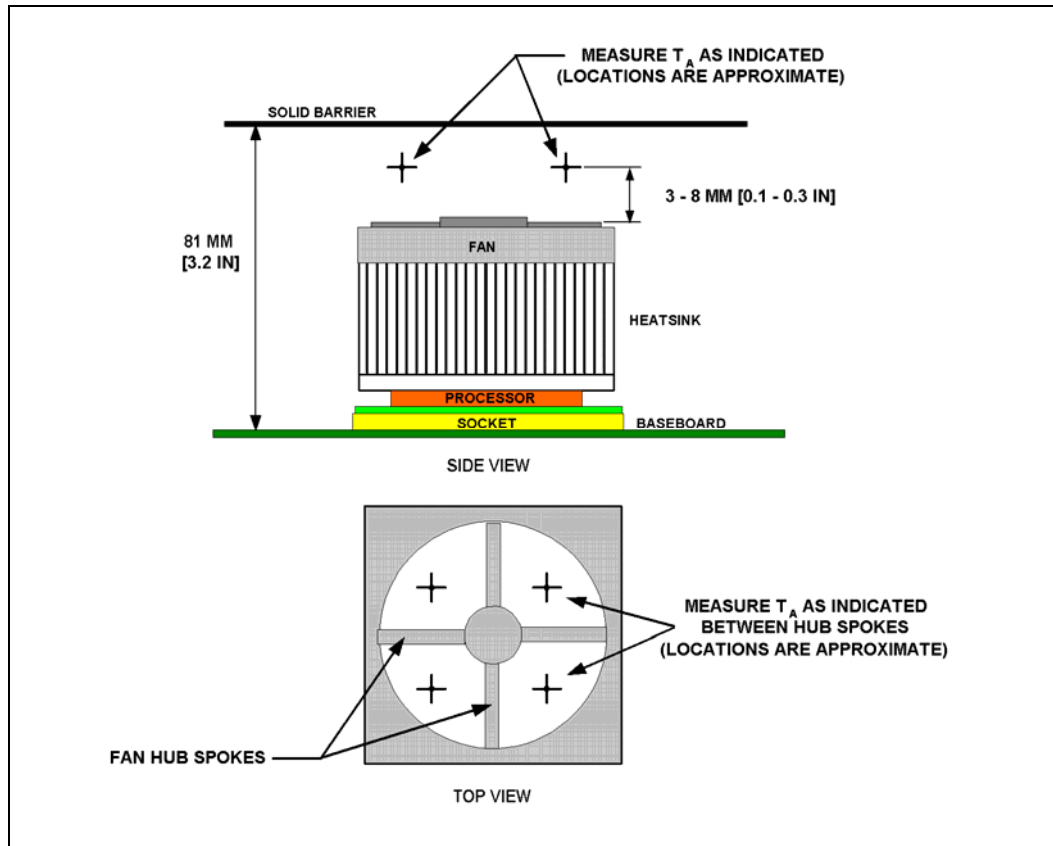
Note: Drawing not to scale.

Figure 6. Locations for Measuring Local Ambient Temperature, Passive Heat Sink
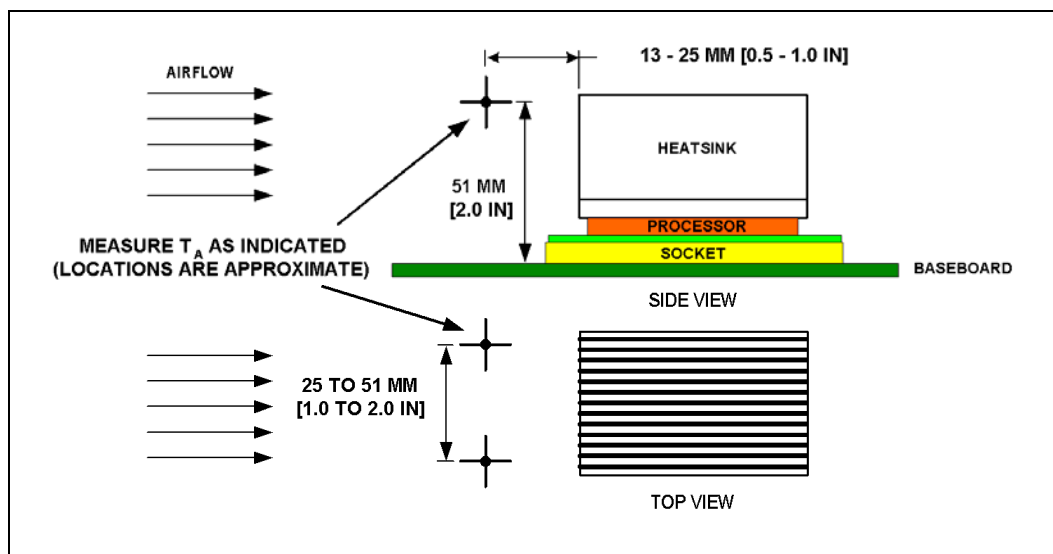
Note: Drawing not to scale.

3.4 Processor Case Temperature Measurement Guidelines

To ensure functionality and reliability, the processor is specified for proper operation when T_C is maintained at or below the thermal profile as listed in the Datasheet. The measurement location for T_C is the geometric center of the IHS. Figure 2 shows the location for T_C measurement.

Special care is required when measuring 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, and the complete measurement system must be routinely checked against known standards. When measuring the temperature of a surface that is at a different temperature from the surrounding local ambient air, errors can be introduced in the measurements. The measurement errors could be caused by poor thermal contact between the junction of the thermocouple and the surface of the integrated heat spreader, heat loss by radiation, convection, by conduction through thermocouple leads, or by contact between the thermocouple cement and the heat sink base.

Appendix C: defines a reference procedure for attaching a thermocouple to the IHS of a 775-Land LGA processor package for T_C measurement. This procedure takes into account the specific features of the 775-Land LGA package and of the LGA775 socket for which it is intended.

4 Thermal Management Logic and the Thermal Monitor Feature

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, and Intel is aggressively pursuing low power design techniques. For example, decreasing the operating voltage, reducing unnecessary transistor activity, and using more power-efficient circuits can significantly reduce processor power consumption.

An on-die thermal management feature called the Thermal Monitor is available on the processor. It provides a thermal management approach to support the continued increases in processor frequency and performance. By using a highly accurate on-die temperature sensing circuit and a fast-acting Thermal Control Circuit (TCC), the processor can rapidly initiate thermal management control. The Thermal Monitor can reduce cooling solution costs by allowing thermal designs to target TDP.

The processor also supports an additional power reduction capability known as Thermal Monitor 2, described in Section 4.2.4.

4.2 Thermal Monitor Implementation

The Thermal Monitor consists of the following components:

- A highly accurate on-die temperature sensing circuit

- A bi-directional signal (PROCHOT#) that indicates if the processor has exceeded its maximum temperature or can be asserted externally to activate the Thermal Control Circuit (TCC) See Section 4.2.1 for more details on user activation of TCC via PROCHOT# signal.

- FORCEPR# signal that will activate the TCC.

- A Thermal Control Circuit that will attempt to reduce processor temperature by rapidly reducing power consumption when the on-die temperature sensor indicates that it has exceeded the maximum operating point.

- Registers to determine the processor thermal status.

4.2.1 PROCHOT# Signal

The primary function of the PROCHOT# signal is to provide an external indication the processor has exceeded its maximum operating temperature. While PROCHOT# is asserted, the TCC will be active. 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.

PROCHOT# can be configured via BIOS as an output or bi-directional signal. As an output, PROCHOT# will go active when the processor temperature of the core exceeds its maximum operating temperature. This indicates the TCC has been activated. As an input, assertion of PROCHOT# will activate the TCC. The TCC will remain active until the system de-asserts PROCHOT#.

If PROCHOT# is configured as an output only, the FORCEPR# signal can be driven from an external source to activate the TCC. Refer to Section 4.2.2 for details on the FORCEPR# signal.

The temperature at which the PROCHOT# signal goes active is individually calibrated during manufacturing. The power dissipation of each processor affects the set point temperature. The temperature where PROCHOT# goes active roughly parallels the thermal profile. Once configured, the processor temperature at which the PROCHOT# signal is asserted is not re-configurable.

One application is the thermal protection of voltage regulators (VR). System designers can create a circuit to monitor the VR temperature and activate the TCC when the temperature limit of the VR is reached. By asserting PROCHOT# (pulled-low) or FORCEPR#, which activates the TCC, the VR can cool down as a result of reduced processor power consumption. Bi-directional PROCHOT# can allow VR thermal designs to target maximum sustained current instead of maximum current. Systems should still provide proper cooling for the VR, and rely on bi-directional PROCHOT# signal only as a backup in case of system cooling failure.

Note: A thermal solution designed to meet the thermal profile targets should rarely experience activation of the TCC as indicated by the PROCHOT# signal going active.

4.2.2 FORCEPR# Signal

The FORCEPR# (force power reduction) input can be used by the platform to cause the processor to activate the TCC. If the Thermal Monitor is enabled, the TCC will be activated upon the assertion of the FORCEPR# signal. The TCC will remain active until the system de-asserts FORCEPR#. FORCEPR# is an asynchronous input.

FORCEPR# can be used to thermally protect other system components. To use the VR as an example, when the FORCEPR# pin is asserted, the TCC circuit in the processor will activate, reducing the current consumption of the processor and the corresponding temperature of the VR.

It should be noted that assertion of the FORCEPR# does not automatically assert PROCHOT#. As mentioned previously, the PROCHOT# signal is asserted when a high temperature situation is detected. A minimum pulse width of 500 µs is recommended when the FORCEPR# is asserted by the system. Sustained activation of the FORCEPR# pin may cause noticeable platform performance degradation.

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One application is the thermal protection of voltage regulators (VR). System designers can create a circuit to monitor the VR temperature and activate the TCC when the temperature limit of the VR is reached. By asserting FORCEPR# (pulled-low) and activating the TCC, the VR can cool down as a result of reduced processor power consumption. FORCEPR# can allow VR thermal designs to target maximum sustained current instead of maximum current. Systems should still provide proper cooling for the VR, and rely on FORCEPR# only as a backup in case of system cooling failure. The system thermal design should allow the power delivery circuitry to operate within its temperature specification even while the processor is operating at its Thermal Design Power.

With a properly designed and characterized thermal solution, it is anticipated that FORCEPR# would only be asserted for very short periods of time when running the most power intensive applications. An under-designed thermal solution that is not able to prevent excessive assertion of FORCEPR# in the anticipated ambient environment may cause a noticeable performance loss. Refer to the appropriate platform design guide and the *Voltage Regulator-Down (VRD) 10.1 Design Guide for Desktop Socket 775* for details on implementing the FORCEPR# feature.

4.2.3   Thermal Control Circuit

The Thermal Control Circuit portion of the Thermal Monitor must be enabled for the processor to operate within specifications. The Thermal Monitor's TCC, when active, will attempt to lower the processor temperature by reducing the processor power consumption. In the original implementation of thermal monitor this is done by changing the duty cycle of the internal processor clocks, resulting in a lower effective frequency. When active, the TCC turns the processor clocks off and then back on with a predetermined duty cycle. The duty cycle is processor specific, and is fixed for a particular processor. The maximum time period the clocks are disabled is ~3 µs. This time period is frequency dependent, and higher frequency processors will disable the internal clocks for a shorter time period. Figure 7 illustrates the relationship between the internal processor clocks and PROCHOT#.

Performance counter registers, status bits in model specific registers (MSRs), and the PROCHOT# output pin are available to monitor the Thermal Monitor behavior. Details regarding the use of these registers are described in the appropriate BIOS Writer's Guide.

Figure 7. Concept for Clocks under Thermal Monitor Control
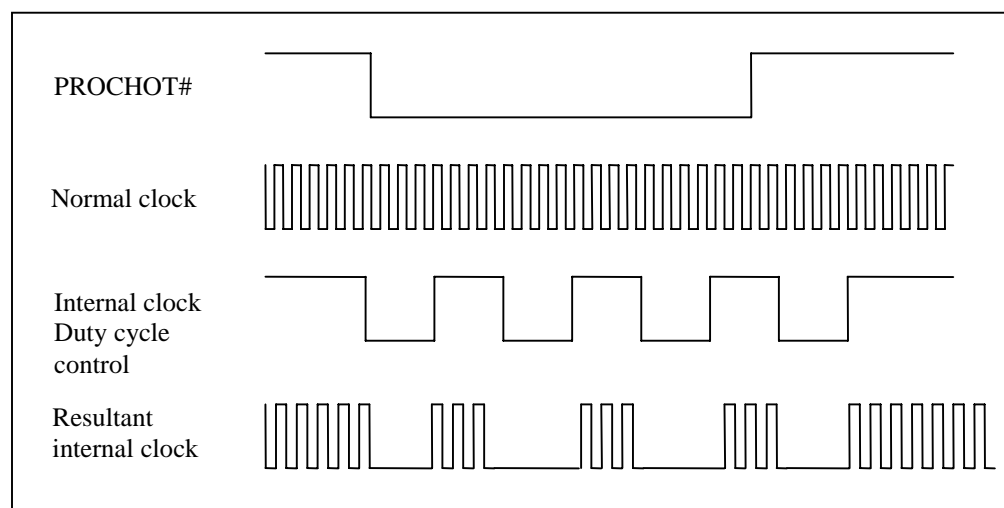
4.2.4   Thermal Monitor 2

The processor supports an enhanced Thermal Control Circuit. In conjunction with the existing Thermal Monitor logic, this capability is known as Thermal Monitor 2. This enhanced TCC provides an efficient means of reducing the power consumption within the processor and limiting the processor temperature.

When Thermal Monitor 2 is enabled, and a high temperature situation is detected, the enhanced TCC will be activated. The enhanced TCC causes the processor to adjust its operating frequency (by dropping the bus-to-core multiplier to its minimum available value) and input voltage identification (VID) value. This combination of reduced frequency and VID results in a reduction in processor power consumption.

A processor enabled for Thermal Monitor 2 includes two operating points, each consisting of a specific operating frequency and voltage. The first operating point represents the normal operating condition for the processor.

The second operating point consists of both a lower operating frequency and voltage. When the TCC is activated, the processor automatically transitions to the new frequency. This transition occurs very rapidly (on the order of 5 microseconds). During the frequency transition, the processor is unable to service any bus requests, and all bus traffic is blocked. Edge-triggered interrupts will be latched and kept pending until the processor resumes operation at the new frequency.

Once the new operating frequency is engaged, the processor will transition to the new core operating voltage by issuing a new VID code to the voltage regulator. The voltage regulator must support VID transitions in order to support Thermal Monitor 2. During the voltage change, it will be necessary to transition through multiple VID codes to reach the target operating voltage. Each step will be one VID table entry (i.e., 12.5 mV steps). The processor continues to execute instructions during the voltage transition. Operation at the lower voltage reduces the power consumption of the processor, providing a temperature reduction.

Once the processor has sufficiently cooled, and a minimum activation time has expired, the operating frequency and voltage transition back to the normal system operating point. Transition of the VID code will occur first, in order to insure proper operation once the processor reaches its normal operating frequency. Refer to Figure 8 for an illustration of this ordering.

Figure 8. Thermal Monitor 2 Frequency and Voltage Ordering
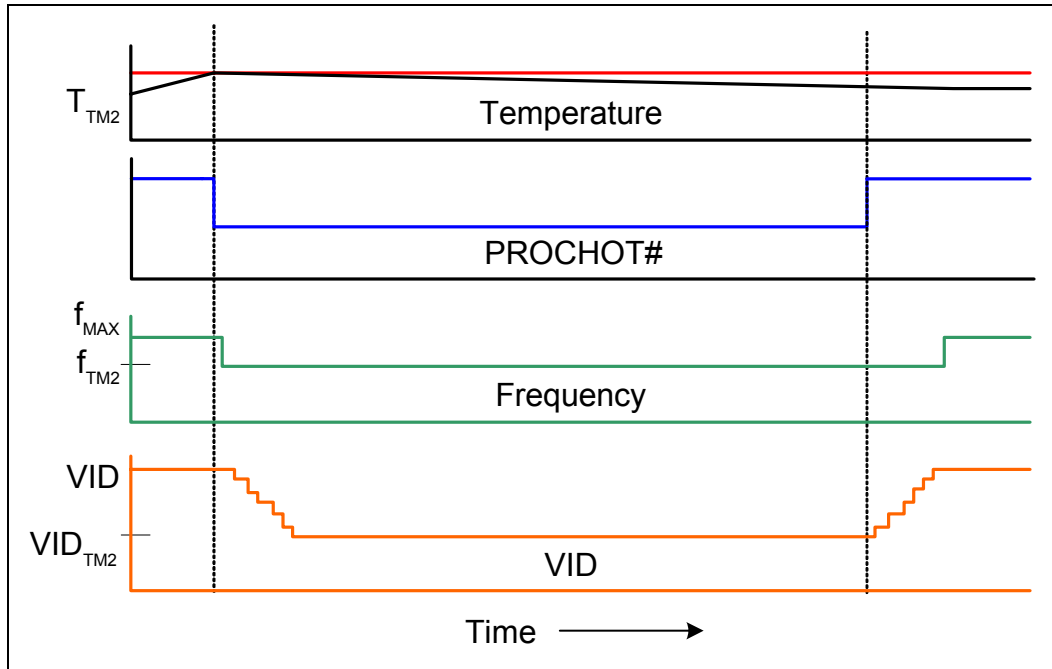
Refer to the Datasheet for further information on Thermal Monitor 2.

4.2.5   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. Refer to the appropriate BIOS Writer's Guide for specific programming details.

Note: Thermal Monitor must be enabled to ensure proper processor operation.

The Thermal Control Circuit feature can be configured and monitored in a number of ways. OEMs are required 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 attempt 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 after the thermal sensor detects a high temperature, i.e., PROCHOT# assertion. The Thermal Control Circuit and PROCHOT# transition to inactive once the temperature has been reduced below the thermal trip point, although a small time-based hysteresis 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.

The power reduction mechanism of thermal monitor can also be activated manually using an "on-demand" mode. Refer to Section 4.2.6 for details on this feature.

4.2.6   On-Demand Mode

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 thermal solution investigations or for performance implication studies. When using the MSRs to activate the on-demand clock modulation 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 the clocks are disabled remains constant, and the time period the clocks are enabled is adjusted to achieve the desired ratio. For example, if the clock disable period is 3 µs, and a duty cycle of ¼ (25%) is selected, the clock on time would be reduced to approximately 1 µs [on time (1 µs) ÷ total cycle time (3 + 1) µs = ¼ duty cycle]. Similarly, for a duty cycle of 7/8 (87.5%), the clock on time would be extended to 21 µs [21 ÷ (21 + 3) = 7/8 duty cycle].

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

Note: On-demand mode can not activate the power reduction mechanism of Thermal Monitor 2.

4.2.7   System Considerations

Intel requires the Thermal Monitor and Thermal Control Circuit to be enabled for all processors. The thermal control circuit is intended to protect against short term thermal excursions that exceed the capability of a well-designed processor thermal solution. Thermal Monitor should not be relied upon to compensate for a thermal solution that does not meet the thermal profile up to the thermal design power (TDP).

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 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.

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A system designed to meet the thermal profile at TDP and T_{C-MAX} values published in the processor Datasheet greatly reduces the probability of real applications causing the TCC to activate under normal operating conditions. Systems that do not meet these specifications could be subject to more frequent activation of the TCC, depending on 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 the processor Datasheet and to Section 4.2.10 of this document.

4.2.8   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.

Refer to the *BIOS Writer's Guide* for specific programming details on the thermal control circuit enabling sequence.

4.2.9   On-Die Thermal Diode

There are two independent thermal sensing devices in the processor. One is the on-die thermal diode, and the other is in the temperature sensor used for the Thermal Monitor (and Thermal Monitor 2) and for THERMTRIP#. The Thermal Monitor's temperature sensor and the on-die thermal diode are independent and physically isolated devices. 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.

The temperature distribution across the die may result in significant temperature differences between the on-die thermal diode and the Thermal Monitor's temperature sensor. This temperature variability across the die is highly dependent on the application being run. As a result, it is not possible to predict the activation of the Thermal Control Circuit by monitoring the on-die thermal diode.

System integrators should note that there is no defined correlation between the on-die thermal diode and the processor case temperature. The temperature distribution across the die is affected by the power being dissipated, type of activity the processor is performing (e.g., integer or floating point intensive), and the leakage current. The dynamic and independent nature of these effects makes it difficult to provide a meaningful correlation for the processor population.

System integrators that plan on using the thermal diode for system or component level fan control in order to optimize acoustics should refer to the "Acoustic Fan Control" section of the *Intel®* *Pentium® D Processor, Intel® Pentium® Processor Extreme Edition and Intel® Pentium® 4* *Processor Thermal and Mechanical Design Guidelines (TMDG) For the Intel® Pentium® D* *Processor 800Δ and 900Δ Sequences, Intel® Pentium® Processor Extreme Edition 840Δ and 955Δ* *and Intel® Pentium® 4 Processor 6x1Δ Sequence.*

4.2.9.1　　　　Reading the On-Die Thermal Diode Interface

The on-die thermal diode is accessible from a pair of pins on the processor. The fan speed controller remote thermal sense signals should be connected to these pins per the vendor's recommended layout guidelines. The following table describes these pins.

Table 1. Thermal Diode Interface

Pin Name	Pin Number	Pin Description
THERMDA	AL1	Diode anode
THERMDC	AK1	Diode cathode

4.2.9.2　　　　Correction Factors for the On-Die Thermal Diode

A number of issues can affect the accuracy of the temperature reported by thermal diode sensors. These include the diode ideality and the series resistance, which are characteristics of the processor on-die thermal diode. The processor Datasheet provides the specification for these parameters. The trace layout recommendations between the thermal diode sensors and the processor socket should be followed as listed the vendor datasheets. The design characteristics and usage models of the thermal diode sensors should be reviewed in the manufacturer's datasheets.

The choice of a remote diode sensor measurement component has a significant impact to the accuracy of the reported on-die diode temperature. The component vendors offer components that have stated accuracy of $\pm 3°$ C to $\pm 1°$ C. The improved accuracy generally comes from the number times a current is passed through the diode and the ratios of the currents. Consult the vendor datasheet for details on their measurement process and stated accuracy.

The ideality factor, n, represents the deviation from ideal diode behavior as exemplified by the diode equation:

$$I_{FW} = I_S \times (E^{\,qVD/nkT} - 1)$$

Where I_{FW} = forward bias current, I_S = saturation current, q = electronic charge, V = voltage across the diode, k = Boltzmann Constant, and T = absolute temperature (Kelvin). This equation determines the ideality factor of an individual diode.

For the purposes of determining a correction factor to use with the thermal sensor, the ideality equation can be simplified to the following:

$$T_{ERROR} = T_{MEASURED} \times (1 - N_{ACTUAL} / N_{TRIM})$$

Where T_{ERROR} = correction factor to add to the reported temperature, $T_{MEASURED}$ = temperature reported by the thermal sensor (Kelvin), N_{ACTUAL} = the ideality of the on-die thermal diode, N_{TRIM} = the assumed ideality used by the thermal sensor. For the range of temperatures where the thermal diode is being measured (30–80° C), this error term is nearly constant.

The value of N_{TRIM} is available from the datasheet of the device measuring the processor on die thermal diode. N_{ACTUAL} can be assumed to be typical for this equation.

The series resistance, R_T, is provided to allow for a more accurate measurement of the on-die thermal diode temperature. R_T, as defined, includes the Lands and processor package but does not include any socket resistance or board trace resistance between the socket and the external remote diode thermal sensor. R_T can be used by remote diode thermal sensors with a register that can add the offset. Some vendors offer a feature that automatically cancels the series resistance. To manually calculate T_{ERROR}, use the following equation:

$$T_{ERROR} = (R_T \times (N - 1) \times I_{FWmin}) / (nk/q \times I_N \ \ln N)$$

Where T_{ERROR} = sensor temperature error, N = sensor current ratio, k = Boltzmann Constant, q = electronic charge.

4.2.10   THERMTRIP# Signal

In the event of a catastrophic cooling failure, the processor will automatically shut down when the silicon temperature has reached its operating limit. At this point the system bus signal THERMTRIP# goes active and power must be removed from the processor. THERMTRIP# activation is independent of processor activity and does not generate any bus cycles. Refer to the processor Datasheet for more information about THERMTRIP#.

The temperature where the THERMTRIP# signal goes active is individually calibrated during manufacturing, and is roughly parallel to the thermal profile and greater than the PROCHOT# activation temperature. Once configured, the temperature at which the THERMTRIP# signal is asserted is neither re-configurable nor accessible to the system.

4.2.11   Cooling System Failure Warning

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 normal system shutdown. If no thermal management action is taken, the silicon temperature may exceed the operating limits, causing THERMTRIP# to activate and shut down the processor. Regardless of the system design requirements or thermal solution ability, the Thermal Monitor feature must still be enabled to ensure proper processor operation.

5 Intel Reference Thermal Solution

5.1 Thermal Solution Requirements

The thermal performance required for the heat sink is determined by calculating the case-to-ambient thermal characterization parameter, Ψ_{CA}, as explained in Section 3.1. This is a basic thermal engineering parameter that may be used to evaluate and compare different thermal solutions in similar boundary conditions. For the Intel® Pentium® 4 Processor 651 with Hyper-Threading Technology[†] for Embedded Applications, an example of how Ψ_{CA} is calculated is shown in the following equation.

Equation 2 Case-to-Ambient Thermal Characterization Parameter

$$\Psi_{CA} = \frac{T_{C\max}(°C) - T_{LA}(°C)}{TDP(W)} = \frac{69.0°C - 38°C}{86W} = 0.360\frac{°C}{W}$$

In this calculation, $T_{C\,max}$ and TDP are taken from the thermal profile specification in the *Intel® Pentium® 4 Processor 6x1$^\Delta$ Sequence Datasheet On 65 nm Process in the 775-land LGA Package and supporting Intel® Extended Memory 64 Technology$^\Phi$*. It is important to note that in this calculation the $T_{C\,max}$ and TDP are constant, while Ψ_{CA} will vary according to the local ambient temperature (T_{LA}).

Table 2 shows an example of required thermal characterization parameters for the thermal solution at various local ambient temperatures. This table uses the $T_{C\,max}$ and TDP from the *Intel® Pentium® 4 Processor 6x1$^\Delta$ Sequence Datasheet On 65 nm Process in the 775-land LGA Package and supporting Intel® Extended Memory 64 Technology$^\Phi$*. These numbers are subject to change and in case of conflict the specifications in the processor Datasheet supersede the $T_{C\,max}$ and TDP specifications in this document.

Table 2 Thermal Characterization Parameter at Various T_{LA} Values

Processor in the 775-Land Package			Required Ψ_{CA} (°C/W) of Thermal Solution at T_{LA} = (°C)			
Frequency (GHz)	TDP (W)	$T_{C\,Max}$ (°C)	44.1	40	35	30
3.4	86	69.0	0.290	0.337	0.395	0.453

Figure 9 further illustrates the required thermal characterization parameter for the Intel® Pentium® 4 Processor 651 with Hyper-Threading Technology[†] for Embedded Applications at various operating ambient temperatures. The thermal solution design must have a Ψ_{CA} less than the values shown for the given local ambient temperature.

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**Figure 9 Thermal Characterization Parameters for Various Operating Conditions**
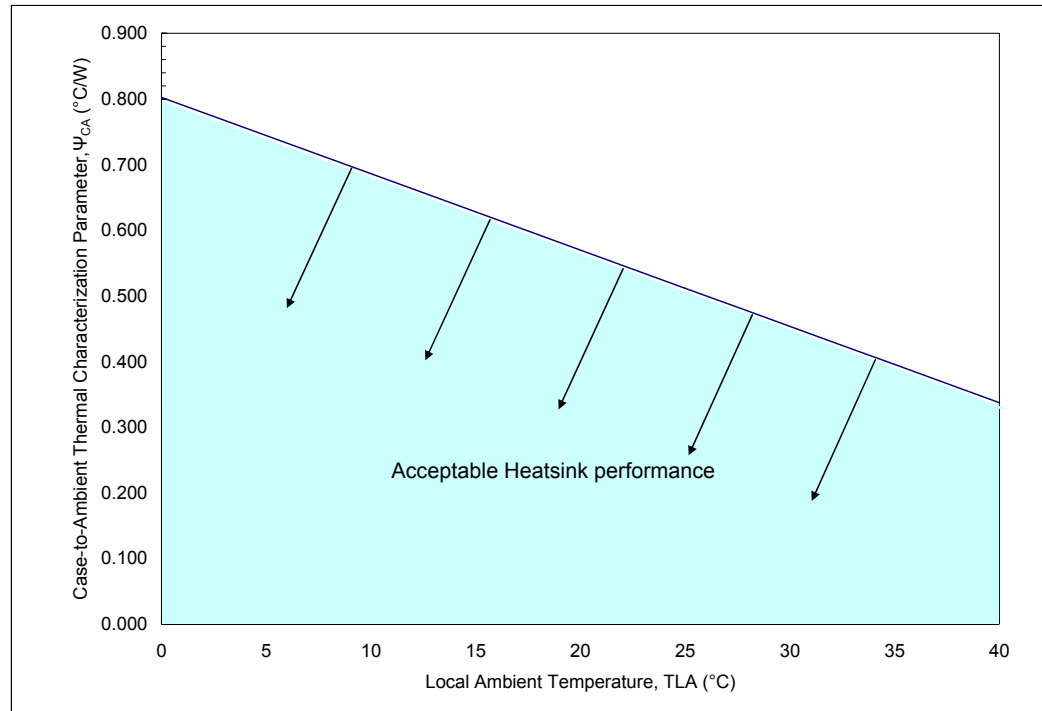
5.2   1U Form Factor

Thermal solution design for the Intel Pentium 4 Processor 651 with HT Technology in the 1U form factor is very challenging. Due to limited volume for the heat sink (mainly in direction of heat sink height) and the available amount of airflow, system designers may have to make some tradeoffs in the system boundary condition requirements (i.e., maximum T_{LA}, acoustic requirements, etc.) in order to meet the processor's thermal requirements. The entire thermal solution from the heat sink design, chassis configuration, and airflow source needs to be optimized in order to obtain the best performing solution.

Intel has worked with a third party vendor to enable a heat sink design for the Intel Pentium 4 Processor 651 with HT Technology for the 1U form factor. This design was optimized for the 1U form factor within the available volume for the thermal solution. The motherboard component keep-ins can be seen in Figure 43 and Figure 44.

This solution requires 100% of the airflow to be ducted through the heat sink fins in order to prevent heat sink bypass. It is a copper base and copper fin heat sink attached to the motherboard with the use of a backplate. This solution is shown in Figure 10.

Figure 10 1U Copper Heat Sink
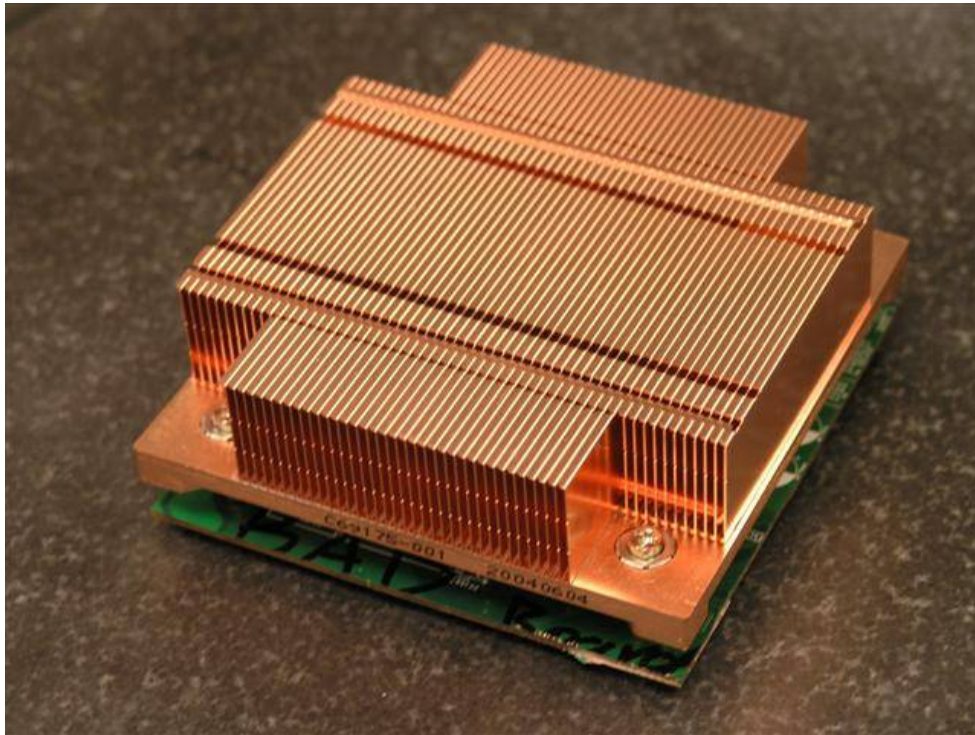
Based on lab test data, this heat sink has an estimated sink-to-ambient (Ψ_{SA}) performance of 0.246 °C/W and an estimated case-to-ambient (Ψ_{CA}) performance of 0.346 °C/W with 18 CFM of airflow through the heat sink fins. This will allow a maximum T_{LA} of 39° C and meet the processor's Thermal Profile specification as described in the processor Datasheet. The estimated performance for additional airflows is shown in Figure 11.

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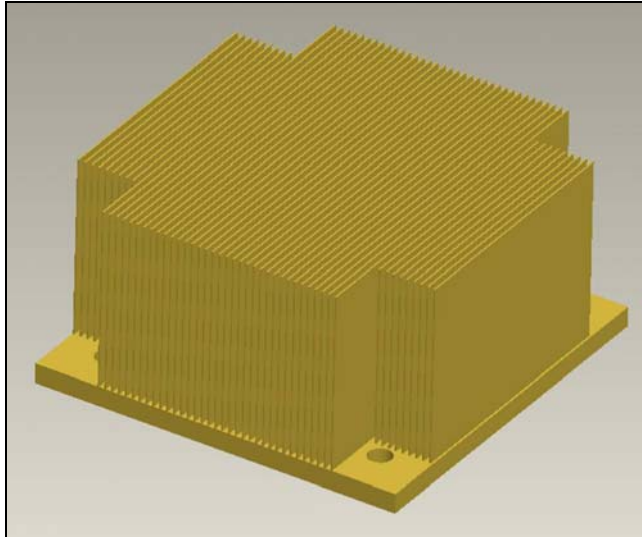**Figure 11 1U Heat Sink Performance**
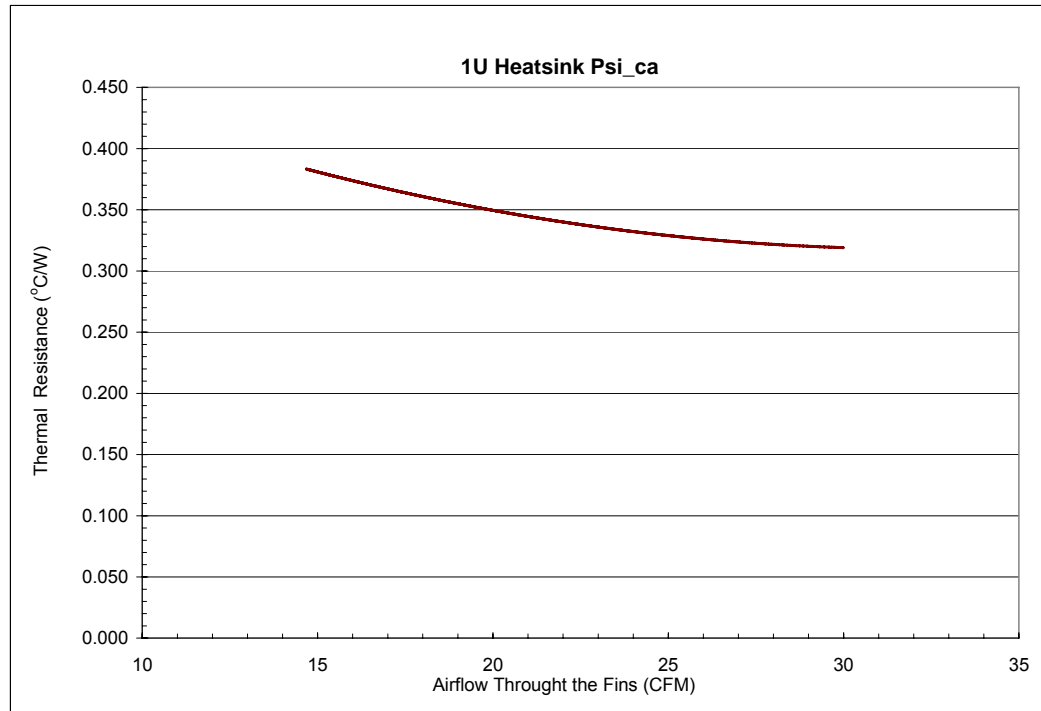
The performance of the heat sink could improve with more airflow. However, the final intended thermal solution including heat sink, airflow source, TIM, and attach mechanism must be validated by system integrators.

Developers who wish to design thermal solutions for the Intel Pentium 4 Processor 651 with HT Technology need to ensure that they meet the processor thermal specifications as stated in the processor datasheet, and follow the recommended motherboard component keep-out as shown in Figure 43 and Figure 44. This keep-out will ensure that the processor thermal solution will not interfere with the voltage regulator components. In addition, a thermal solution design must meet the maximum component heights as specified by the 1U *Thin Electronics Bay Specifications* located at http://www.ssiforum.org.

5.3 2U Form Factor

Intel has developed a reference thermal solution design for the Intel Pentium 4 Processor 651 with HT Technology in the 2U form factor. This design was optimized for the 2U form factor within the available volume for the thermal solution. The motherboard component keep-outs can be seen in Figure 43 and Figure 44.

This solution requires 100 percent of the airflow to be ducted through the heat sink fins in order to prevent heat sink bypass. It is a copper base and copper fin heat sink that is attached to the motherboard with the use of a backplate. This solution is shown in Figure 12.

Figure 12 2U Copper Heat Sink

Based on lab test data, this heat sink has an estimated to have a sink-to-ambient thermal performance (Ψ_{SA}) of 0.211 °C/W and an estimated case-to-ambient thermal performance (Ψ_{CA}) of 0.311 °C/W with 25 CFM of airflow through the fins. This will allow a maximum T_{LA} of 42° C and meet the processor's Thermal Profile specification as described in the processor Datasheet. The estimated performance of the heat sink at additional airflows is shown in Figure 13.

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Figure 13 2U Heat Sink Performance
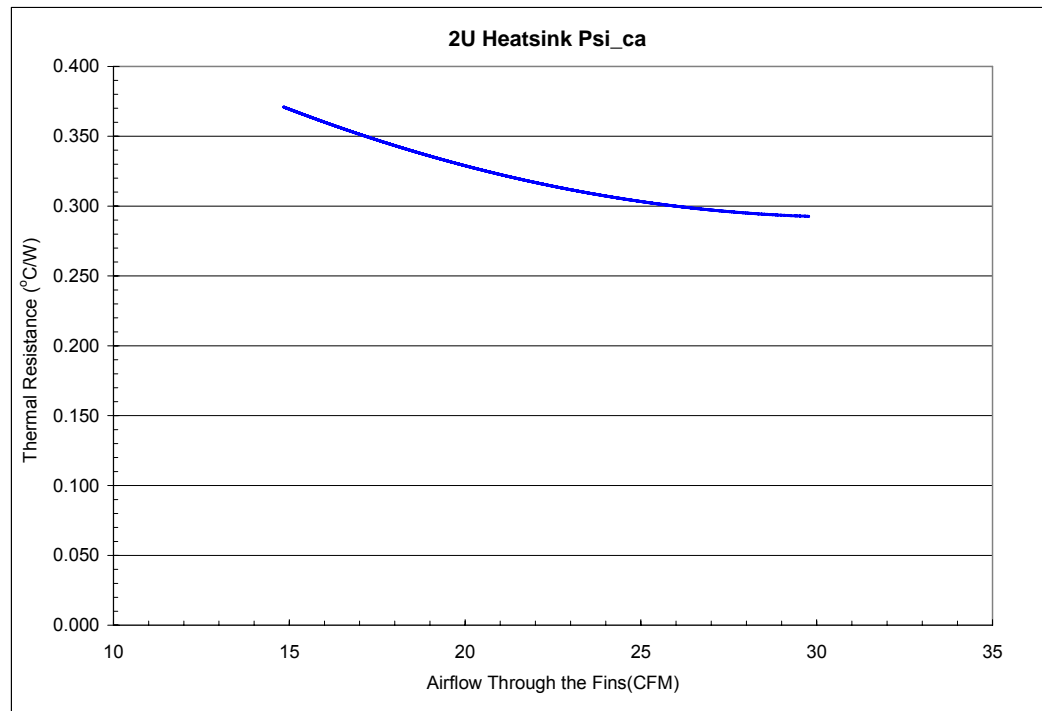
The performance of the heat sink will vary depending on the amount airflow provided. The final intended thermal solution including heat sink, airflow source, TIM, and attach mechanism must be validated by system integrators.

Developers who wish to design thermal solutions for the Intel Pentium 4 Processor 651 with HT Technology must ensure that they meet the processor thermal specifications as stated in the processor datasheet, and follow the recommended motherboard component keep-out as shown in Figure 43 and Figure 44. This keep-out will ensure that the processor thermal solution will not interfere with the voltage regulator components. In addition, a thermal solution design must meet the maximum component heights as specified by the 2U *Thin Electronics Bay Specifications* located at http://www.ssiforum.org.

5.4 Reference Thermal Mechanical Solution for the Intel® Pentium® 4 Processor in the 775-Land Package

For information regarding the Intel Thermal/Mechanical Reference Design thermal solution and design criteria for the ATX and BTX form factor, refer to the *Intel® Pentium® 4 Processor 651 with Hyper-Threading Technology† Thermal Design Guidelines*.

5.5 Altitude

The reference heat sink 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 calculations and measurements 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 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.

5.6 Geometric Envelope for Intel Reference 1U/2U Thermal Mechanical Design

Figure 43 and Figure 44 in Appendix E: give detailed 1U/2U motherboard keep-out information for the reference thermal/mechanical enabling design. These drawings include height restrictions in the enabling component region.

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Appendix A: LGA775 Socket Heat Sink Loading

A.1 LGA775 Socket Heat Sink Considerations

Heat sink clip load is traditionally used for:

- Mechanical performance in mechanical shock and vibration

- Thermal interface performance
  — Required preload depends on TIM
  — Preload can be low for thermal grease

In addition to mechanical performance in shock and vibration and TIM performance, the LGA775 socket requires a minimum heat sink preload to protect against fatigue failure of the socket solder joints.

Solder ball tensile stress is originally created when, after inserting a processor into the socket, the LGA775 socket load plate is actuated. In addition, solder joint shear stress is caused by coefficient of thermal expansion (CTE) mismatch-induced shear loading. The solder joint compressive axial force (F_{axial}) induced by the heat sink preload helps to reduce the combined joint tensile and shear stress.

Overall, the heat sink required preload is the minimum preload needed to meet all of the above requirements: mechanical shock and vibration, TIM performance, and also LGA775 socket protection against fatigue failure.

A.2 Metric for Heat Sink Preload for Designs Not Compliant with the Intel Reference Design

A.2.1 Heat Sink Preload Requirement Limitations

Heat sink preload by itself is not an appropriate metric for solder joint force across various mechanical designs, and does not take into account, for example, the following factors (not an exhaustive list):

- Heat sink mounting hole span

- Heat sink clip/fastener assembly stiffness and creep

- Board stiffness and creep

- Board stiffness modification by fixtures like backing plate, chassis attach, etc.

Simulation shows that the solder joint force (F_{AXIAL}) is proportional to the board deflection measured along the socket diagonal. The matching of F_{AXIAL} required to protect the LGA775 socket solder joint in temperature cycling is equivalent to matching a target MB deflection.

Therefore, the heat sink preload for LGA775 socket solder joint protection against fatigue failure can be more generally defined as the load required to create a target board downward deflection throughout the life of the product.

This board deflection metric provides guidance for mechanical designs that differ from the reference design for the ATX//µATX form factor.

A.2.2　Motherboard Deflection Metric Definition

Motherboard deflection is measured along either diagonal (refer to Figure 14):

d = dmax – (d1 + d2)/2

d' = dmax – (d'1 + d'2)/2

Configurations in which the deflection is measured are defined in the Table 3 below.

To measure board deflection, follow industry standard procedures (such as IPC) for board deflection measurement. Height gauges and possibly dial gauges may also be used.
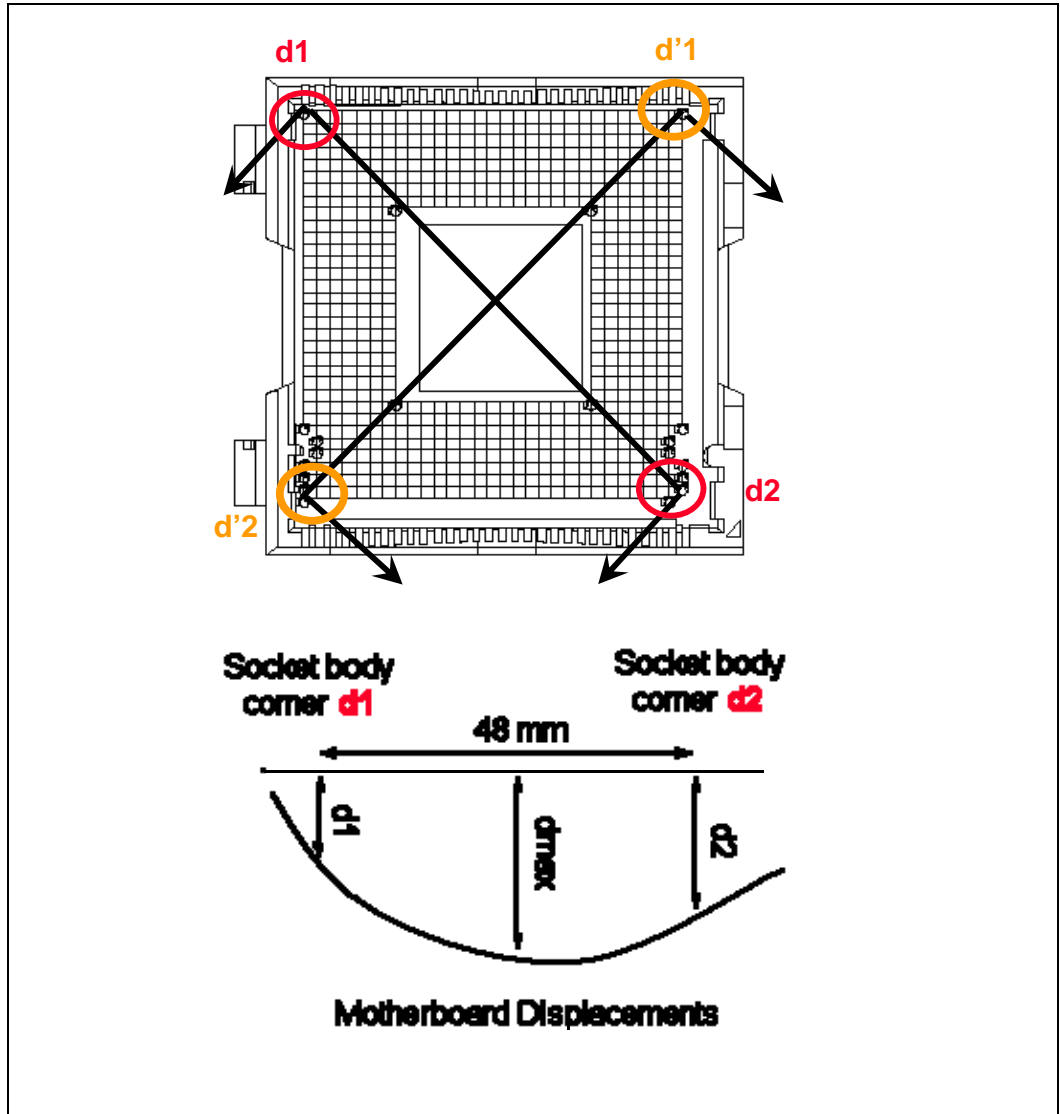
Table 3. Board Deflection Configuration Definitions

Configuration Parameter	Processor + Socket Load Plate	Heat Sink	Parameter Name
d_ref	yes	no	BOL deflection, no preload
d_BOL	yes	yes	BOL deflection with preload
d_EOL	yes	yes	EOL deflection

BOL: Beginning of Life

EOL: End of Life

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Figure 14. Board Deflection Definition

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A.2.3 Board Deflection Limits

Deflection limits for the ATX/µATX form factor are:

$$d\_BOL - d\_ref ≥ 0.09 \text{ mm} \quad \text{and} \quad d\_EOL - d\_ref ≥ 0.15 \text{ mm}$$

and

$$d'\_BOL – d'\_ref ≥ 0.09 \text{ mm} \quad \text{and} \quad d\_EOL' – d\_ref' ≥ 0.15 \text{ mm}$$

NOTES:
1. The heat sink preload must remain within the static load limits defined in the processor Datasheet at all times.
2. Board deflection should not exceed motherboard manufacturer specifications.

A.2.4 Board Deflection Metric Implementation Example

This section is for illustration only, and relies on the following assumptions:

- 72 x 72 mm hole pattern of the reference design.

- Board stiffness = 900 lb/in at BOL, with degradation that simulates board creep over time. Though these values are representative, they may change with selected material and board manufacturing process. Check with your motherboard vendor.

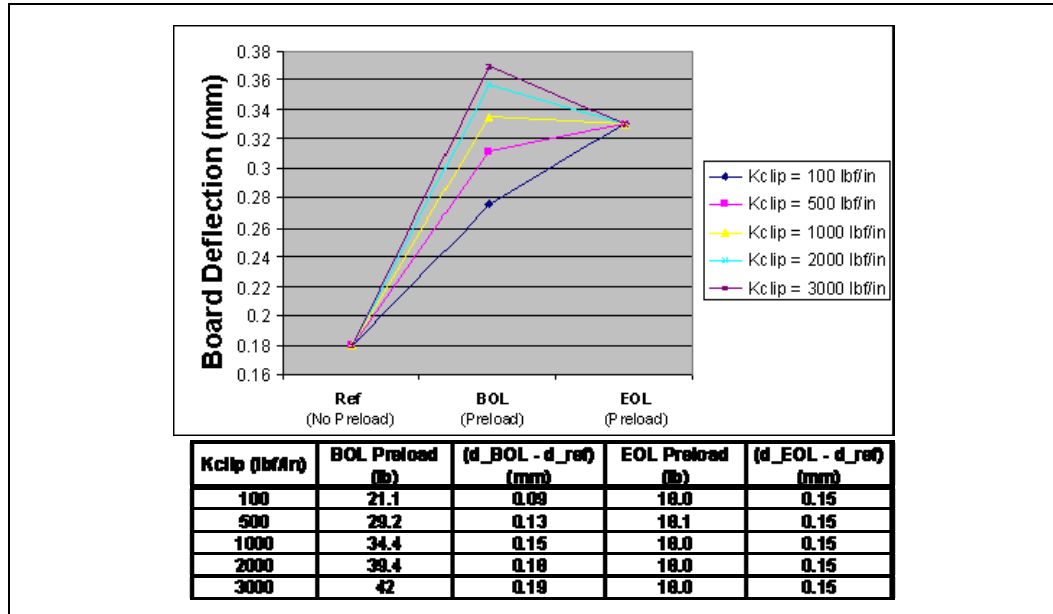- Clip stiffness assumed constant – no creep.

Using Figure 15 below, the heat sink preload at beginning of life is defined to comply with d_EOL – d_ref = 0.15 mm depending on clip stiffness assumption.

Note that the BOL and EOL preload and board deflection differ. This is a result of the creep phenomenon. The example accounts for the creep expected to occur in the motherboard. It assumes no creep to occur in the clip. However, there is a small amount of creep accounted for in the plastic fasteners. This situation is somewhat similar to the Intel Reference Design.

The impact of the creep to the board deflection is a function of the clip stiffness:

- The relatively compliant clips store strain energy in the clip under the BOL preload condition and tend to generate increasing amounts of board deflection as the motherboard creeps under exposure to time and temperature.

- In contrast, the stiffer clips store very little strain energy, and therefore do not generate substantial additional board deflection through life.

Note: Board and clip creep modify board deflection over time, depending on board stiffness, clip stiffness, and selected materials. Designers must define the BOL board deflection that will lead to the correct EOL board deflection.

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Figure 15. Example: Defining Heat Sink Preload Meeting Board Deflection Limit

Kclip (lbf/in)	BOL Preload (lb)	(d_BOL - d_ref) (mm)	EOL Preload (lb)	(d_EOL - d_ref) (mm)
100	21.1	0.09	18.0	0.15
500	29.2	0.13	18.1	0.15
1000	34.4	0.15	18.0	0.15
2000	39.4	0.18	18.0	0.15
3000	42	0.19	18.0	0.15

A.2.5 Additional Considerations

Intel recommends to design to {d_BOL - d_ref = 0.15mm} at BOL when EOL conditions are not known or difficult to assess.

The following information is given for illustration only. It is based on the reference keep-out, assuming there is no fixture that changes board stiffness:

The value for d_ref is expected to be 0.18 mm on average, and be as high as 0.22 mm. As a result, the board should be able to deflect 0.37 mm minimum at BOL.

Additional deflection as high as 0.09 mm may be necessary to account for additional creep effects impacting the board/clip/fastener assembly. As a result, designs could see as much as 0.50 mm total downward board deflection under the socket.

In addition to board deflection, other elements need to be considered to define the space needed for the downward board total displacement under load, like the potential interference of through-hole mount component pin tails of the board with a mechanical fixture on the back of the board.

Note: The heat sink preload must remain below the maximum load limit of the package at all times (refer to processor Datasheet). Board deflection should not exceed motherboard manufacturer specifications.

A.2.5.1 Motherboard Stiffening Considerations

To protect the LGA775 socket solder joint, designers need to drive their mechanical design to:

- Allow downward board deflection to put the socket balls in a desirable force state to protect against fatigue failure of the socket solder joint (refer to sections A.2.1, A.2.2 and A.2.3.
- Prevent board upward bending during mechanical shock events.

- Define load paths that keep the dynamic load applied to the package within specifications published in the processor Datasheet.

Limiting board deflection may be appropriate in some situations like:

- Board bending during shock.

- Board creep with high heat sink preload.

However, the load required to meet the board deflection recommendation (refer to section A.2.3) with a very stiff board may lead to heat sink preloads exceeding package maximum load specifications. For example, such a situation may occur when using a backing plate that is flush with the board in the socket area, and prevents the board from bending underneath the socket.

A.3   Heat Sink Selection Guidelines

Carefully evaluate heat sinks that come with motherboard stiffening devices (like backing plates), and conduct board deflection assessments based on the board deflection metric.

Solutions derived from the reference design comply with the reference heat sink preload; for example:

- The boxed processor.

- The Intel® RCFH-4 reference design available from licensed suppliers (please refer to the *Intel® Pentium® D Processor, Intel® Pentium® Processor Extreme Edition and Intel® Pentium® 4 Processor Thermal and Mechanical Design Guidelines (TMDG) For the Intel® Pentium® D Processor 800$^\Delta$ and 900$^\Delta$ Sequences, Intel® Pentium® Processor Extreme Edition 840$^\Delta$ and 955$^\Delta$ and Intel® Pentium® 4 Processor 6x1$^\Delta$ Sequence* for more information).

Intel will collaborate with vendors participating in its third party test house program to evaluate third party solutions. Vendor information will be available after product launch.

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Appendix B: Thermal Interface Management

Optimizing a heat sink design and achieving the most effective thermal solution requires an understanding of three factors related to the interface between the processor and the heat sink base: bond line thickness, interface material area, and interface material thermal conductivity.

B.1   Bond Line Management

Any gap between the processor integrated heat spreader (IHS) and the heat sink base degrades 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 heat sink 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 heat sink attach clip(s).

B.2   Interface Material Area

The size of the contact area between the processor and the heat sink base will impact the thermal resistance. There is, however, a point of diminishing returns. Unrestrained incremental increases in thermal interface material area do not create measurable improvements in thermal performance.

B.3   Interface Material Performance

Two factors impact the performance of the interface material between the processor and the heat sink base: thermal resistance of the material, and the 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. This value has a significant impact on the thermal performance of the overall thermal solution. The higher the thermal resistance, the less efficient the interface material is at transferring heat, the larger the temperature drop will be across the interface, and the more efficient the thermal solution (heat sink, 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 heat sink retention mechanism, to spread and fill the gap between the processor and the heat sink. Since air is an extremely poor thermal conductor, the more completely the interface material fills the gaps, the less the temperature drops 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.

Appendix C: Case Temperature Reference Metrology

C.1   Objective and Scope

This appendix defines a reference procedure for attaching a thermocouple to the IHS of a 775-Land LGA package for T_C measurement. This procedure takes into account the specific features of the 775-Land LGA package and of the LGA775 socket for which it is intended. This procedure is applicable for both Thermal Test Vehicles (TTV) and functional processors. The recommended equipment for the reference thermocouple installation, including tools and part numbers, are also provided. In addition, a video, *Thermocouple Attach Using Solder* is available that shows the process.

Note: This procedure is applicable only to processors that comply with the 2005 Performance or Mainstream / Value FMB. The T_C measurements from this metrology are not compatible with processor specifications based on 2004 FMB targets.

C.2   Supporting Test Equipment

To apply the reference thermocouple attach procedure, it is recommended to use the equipment (or equivalent) given in the table below.

Table 4. Supporting Test Equipment

Item	Description	Part Number
Measurement and Output		
Microscope	Olympus* light microscope or equivalent	SZ-40
DMM	Digital multimeter for resistance measurement	Fluke 79 series
Thermal Meter	Hand-held thermocouple meter	Multiple vendors
Solder Station (see note 1 for ordering information)		
Heater Block	Heater assembly to reflow solder on IHS	30330
Heater	Watlow* 120V 150W Firerod*	0212G G1A38-L12
Transformer	Superior Electric* Powerstat* transformer	05F857
Miscellaneous Hardware		
Solder	Indium* Corp. of America Alloy 57BI / 42SN / 1AG 0.010 Diameter	52124
Flux	Indium Corp. of America	5RMA
Loctite* 498 Adhesive	Super glue with thermal characteristics	49850

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Item	Description	Part Number
Adhesive Accelerator	Loctite 7452 for fast glue curing	18490
Kapton* Tape	Holds thermocouple in place	Not available
Thermocouple	Omega*, 36 gauge, "T" Type (see note 2 for ordering information)	OSK2K1280/5SRTC-TT-T-36-72
Calibration and Control		
Ice Point Cell	Omega, stable 0º C temperature source for calibration and offset	TRCIII
Hot Point Cell	Omega, temperature source to control and understand meter slope gain	CL950-A-110

NOTES:
1. The solder station consisting of the heater block, heater, press, and transformer is available from Jemelco* Engineering, 480-804-9514.
2. This part number is a custom part with the specified insulation trimming and packaging requirements necessary for quality thermocouple attachment, See Figure 16. Order from Omega, Anthony Alvarez, direct phone: (203) 359-7671; direct fax: (203) 968-7142; e-mail: aalvarez@omega.com.

Figure 16. Omega Thermocouple
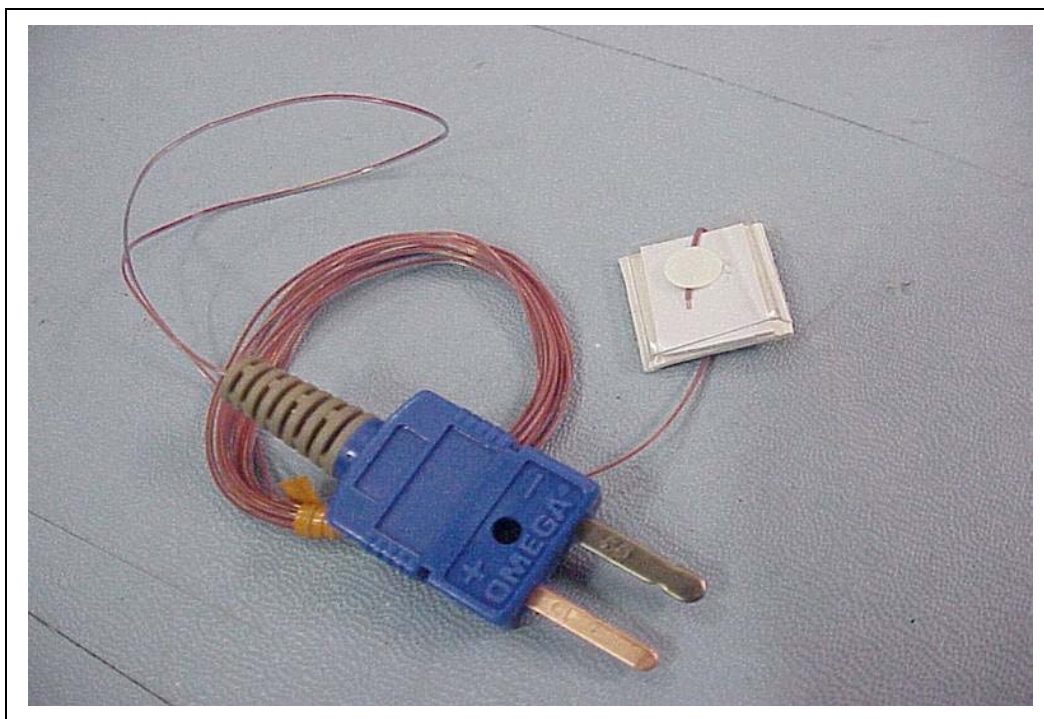
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C.3 Thermal Calibration and Controls

It is recommended that full and routine calibration of temperature measurement equipment be performed before attempting to perform temperature case measurement of TTVs and live products. Intel recommends checking the meter probe set against known standards. This should be done at 0º C (using ice bath or other stable temperature source) and at an elevated temperature, around 80º C (using an appropriate temperature source).

Wire gauge and length also should be considered, as some less expensive measurement systems are heavily impacted by impedance. There are numerous resources available throughout the industry to assist with implementation of proper controls for thermal measurements.

Note: It is recommended to follow company standard procedures and wear safety items like glasses for cutting the IHS and gloves for chemical handling. Please ask your Intel field sales representative if you need assistance to groove and/or install a thermocouple according to the reference process.

C.4 Cutting the IHS Groove

To achieve accurate thermal readings, the thermocouple bead must be inserted into a groove cut in the IHS, as shown in the drawing in Figure 17. This section describes the procedure for cutting the groove.

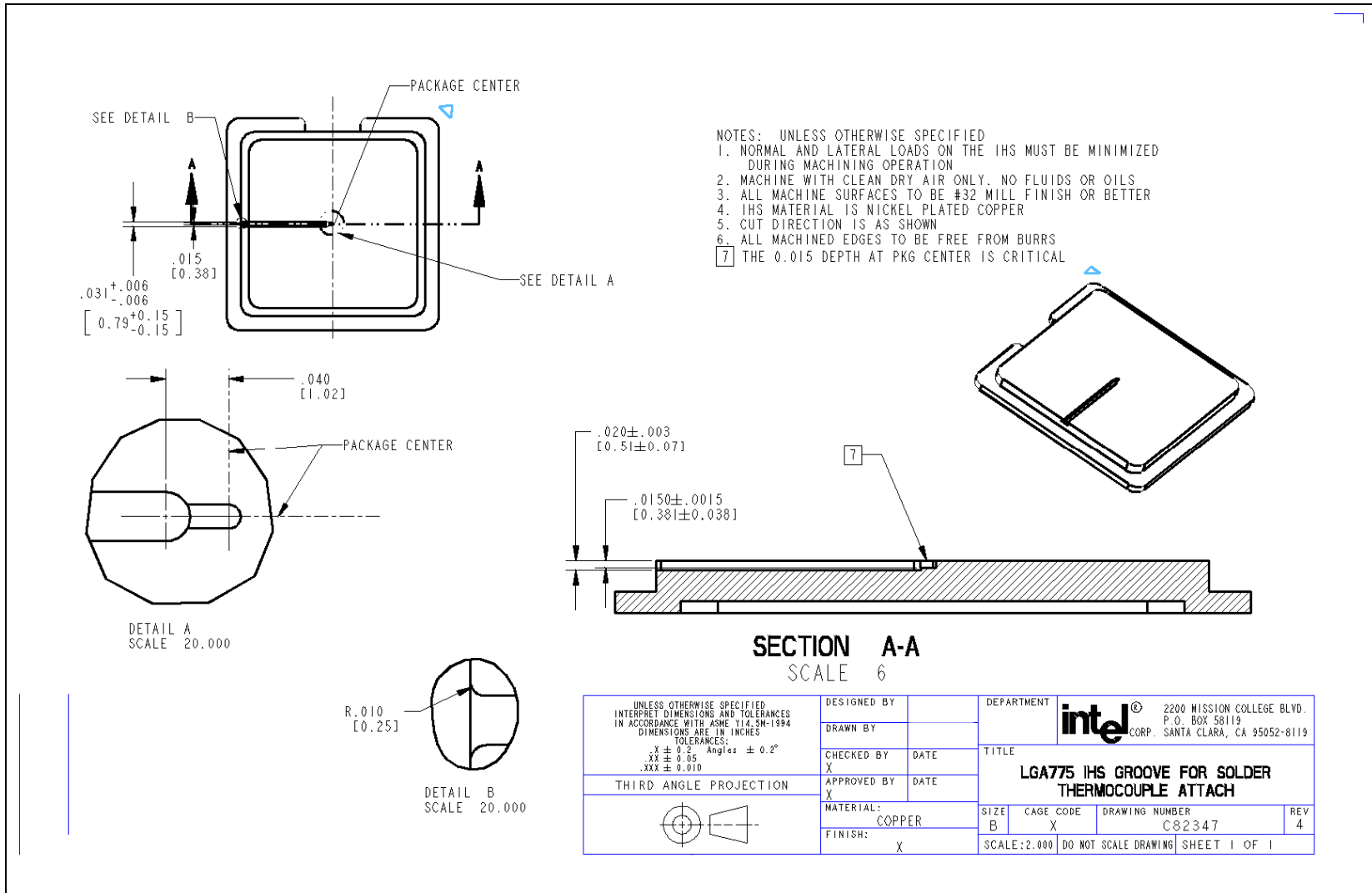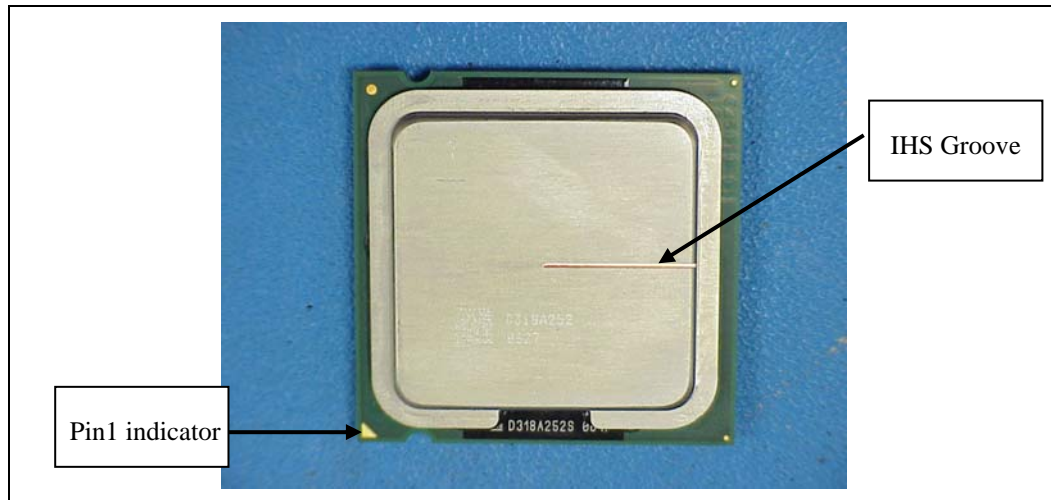**Figure 17. 775-Land LGA Package Reference Groove Drawing**

Figure 18 shows the orientation of the groove relative to the package pin 1 indicator (gold triangle in one corner of the package) for the 775-Land LGA package IHS.

Figure 18. IHS Groove Orientation

When the processor is installed in the LGA775 socket, the groove is perpendicular to the socket load lever, and on the opposite side of the lever, as shown Figure 19.

Figure 19. IHS Groove Orientation Relative to the LGA775 Socket
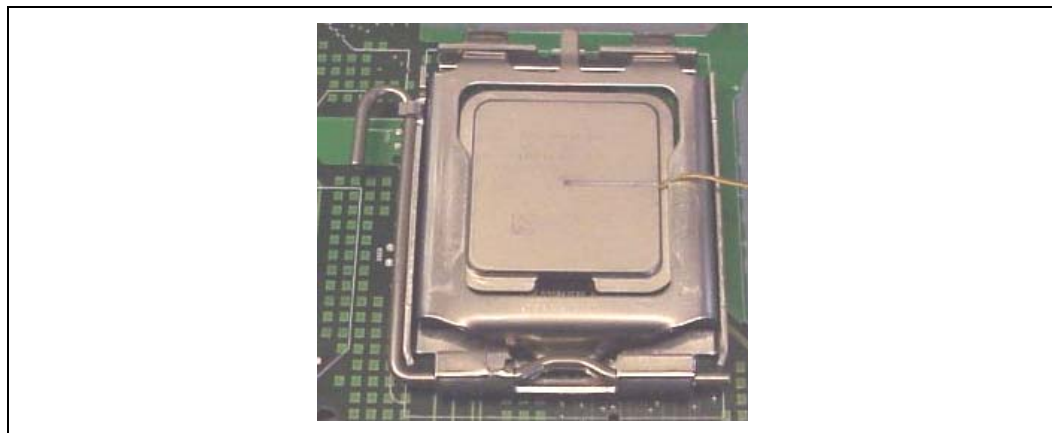
Select a machine shop that is capable of holding drawing-specified tolerances. IHS groove geometry is critical for repeatable placement of the thermocouple bead, ensuring precise thermal measurements. The specified dimensions minimize the impact of the groove on the IHS under the socket load. A larger groove may cause the IHS to warp under the socket load such that it does not represent the performance of an ungrooved IHS on production packages.

Inspect parts for compliance to specifications before accepting from the machine shop. Especially critical is the 0.015 depth at package center, as shown in Figure 17.

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C.5 Thermocouple Attachment Procedure

The procedure to attach a thermocouple with solder takes as little as 15 minutes to complete. Before proceeding, turn on the solder block heater, as it can take up to 30 minutes to reach the target temperature of 153–155° C.

Note: To avoid damage to the TTV or processor, ensure the heater temperature does not exceed 155° C.

As a complement to the written procedure, a video, *Thermocouple Attach Using Solder* is available.

C.5.1 Thermocouple Conditioning and Preparation

1. Utilize a calibrated thermocouple as specified in sections C.2 and C.3.
2. Under a microscope, verify the thermocouple insulation meets the quality requirements. The insulation should be about 1/16 inch (0.62 ± 0.030) from the end of the bead (Figure 20).

**Figure 20. Inspection of Insulation on Thermocouple**
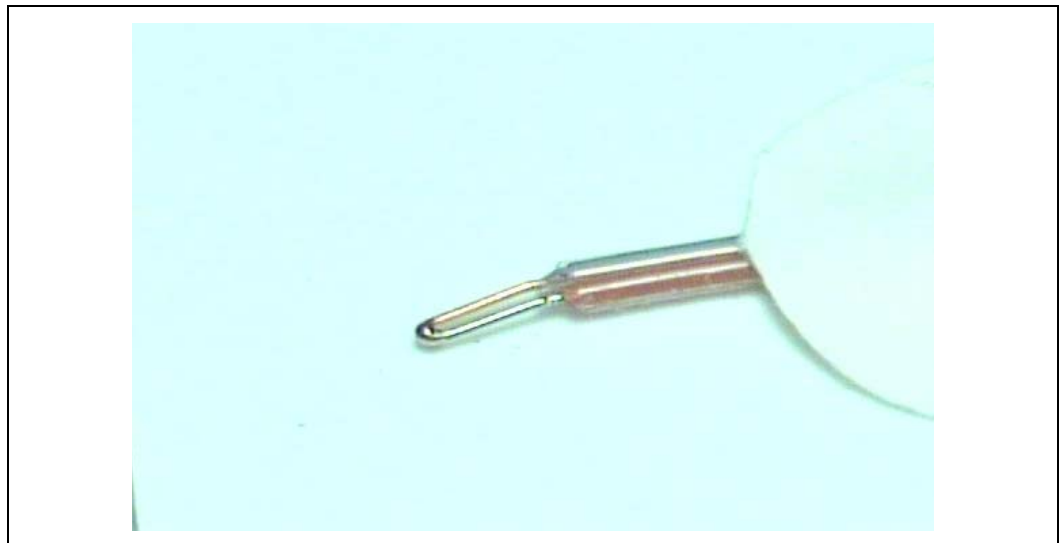
3. Measure the thermocouple resistance by holding both contacts on the connector to one DMM probe and the tip of thermocouple to the other DMM probe. (The measurement should be about 3.0 ohms for a 36 gauge type T thermocouple.)
4. Straighten the wire for about 38 mm [1.5 inch] from the bead.
5. Using the microscope and tweezers, bend the tip of the thermocouple at approximately a 10 degree angle for about 0.8 mm [1/32 inch] from the tip (Figure 21).

Figure 21. Bending the Tip of the Thermocouple
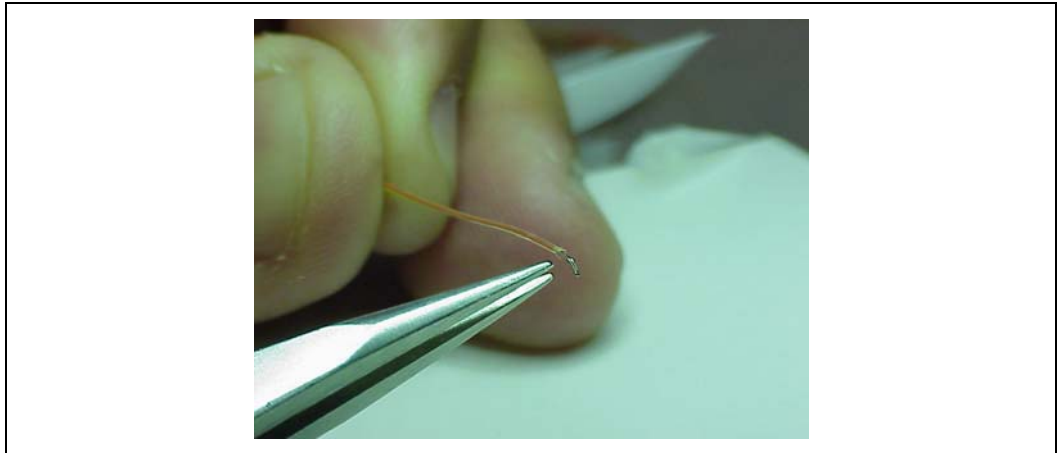

C.5.2   Attaching Thermocouple to the IHS

1. Clean the groove and IHS with isopropyl alcohol (IPA) and a lint-free cloth, removing all residues prior to thermocouple attachment.

2. Place the thermocouple wire inside the groove, letting the exposed wire and bead extend about 1.5 mm [0.030 inch] past the end of groove. Secure it with Kapton tape (Figure 22). Clean the IHS with a swab and IPA.

3. Verify under the microscope that the thermocouple wires are straight and parallel in the groove and that the bead is still bent.

Figure 22. Securing Thermocouple Wires with Kapton Tape prior to Attachment
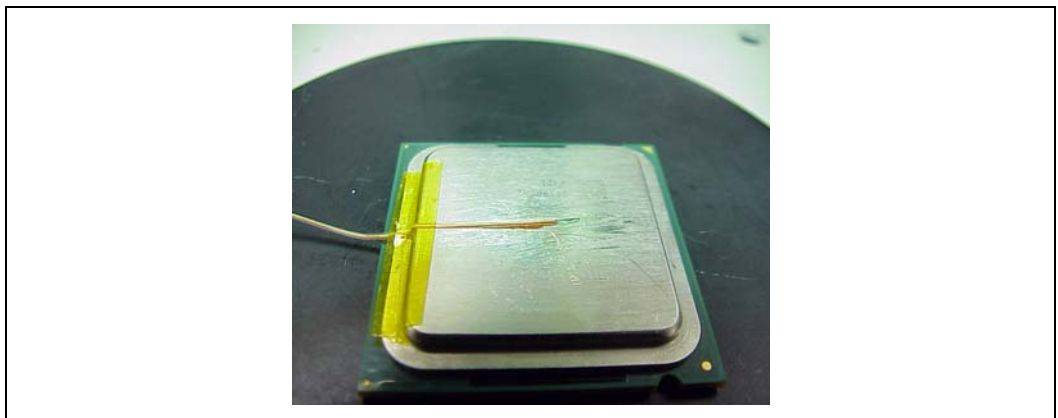
4. Lift the wire at the middle of groove with tweezers and bend the front of the wire to place the thermocouple in the groove, ensuring the tip is in contact with the end and bottom of the groove in the IHS (Figure 23-A and B).

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Figure 23. Thermocouple Bead Placement

(A)

(B)
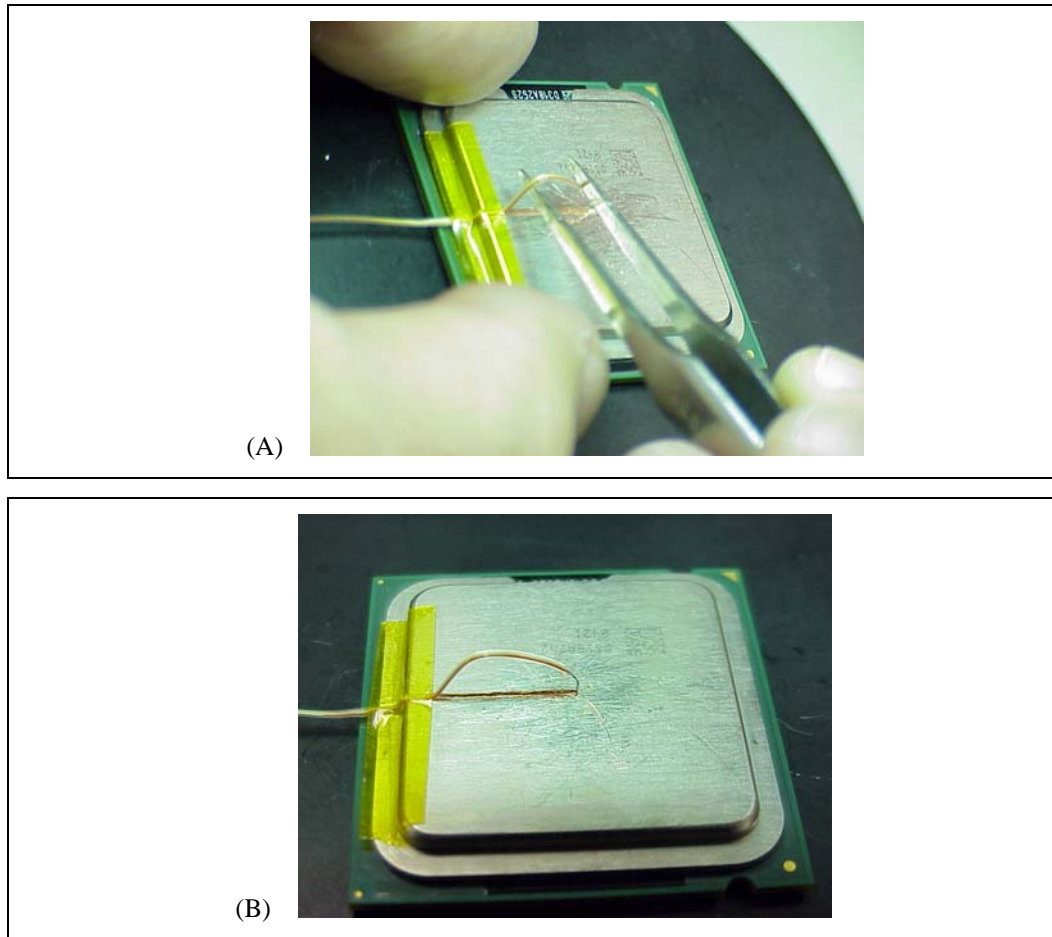
5. Place the package under the microscope to continue with the procedure. It is also recommended to use a fixture (like a processor tray or a plate) to help hold the unit in place for the rest of the attachment process.

6. While still at the microscope, press the wire down about 6 mm [0.125"] from the thermocouple bead using the tweezers or your finger. Place a piece of Kapton tape to hold the wire inside the groove (Figure 24). Refer to Figure 25 for a side cutaway view showing detailed bead placement.

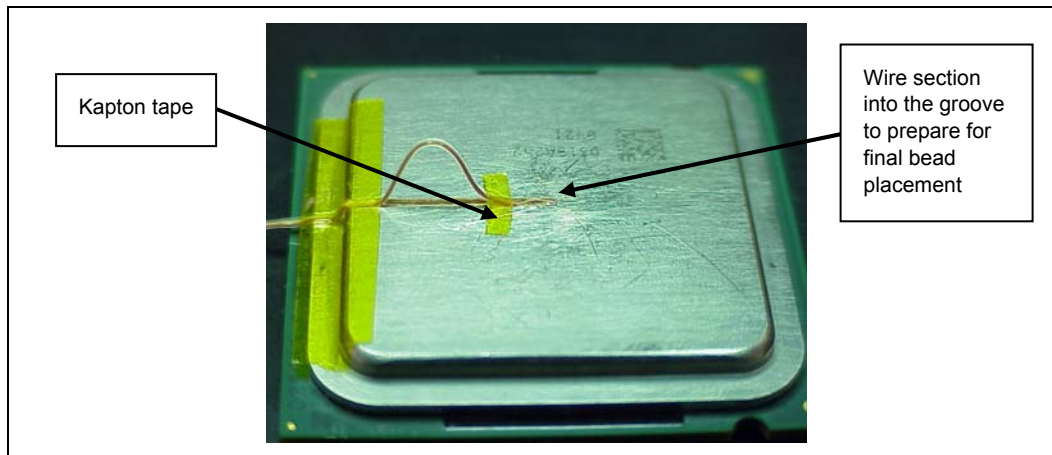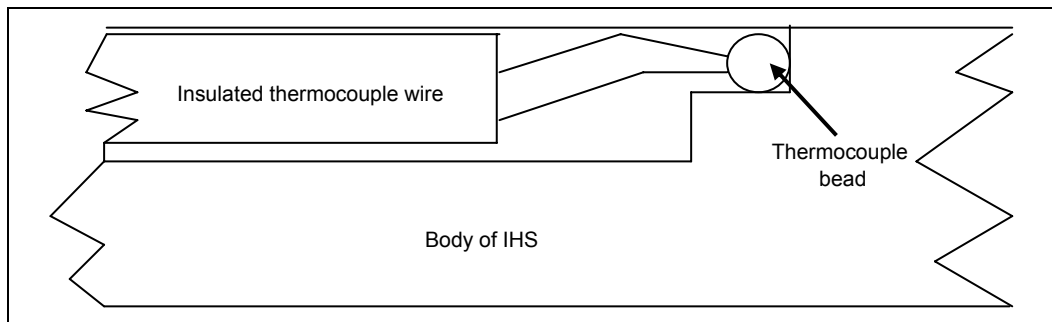**Figure 24. Position Bead on the Groove Step**

Kapton tape

Wire section into the groove to prepare for final bead placement

Figure 25. Detailed Thermocouple Bead Placement

Insulated thermocouple wire
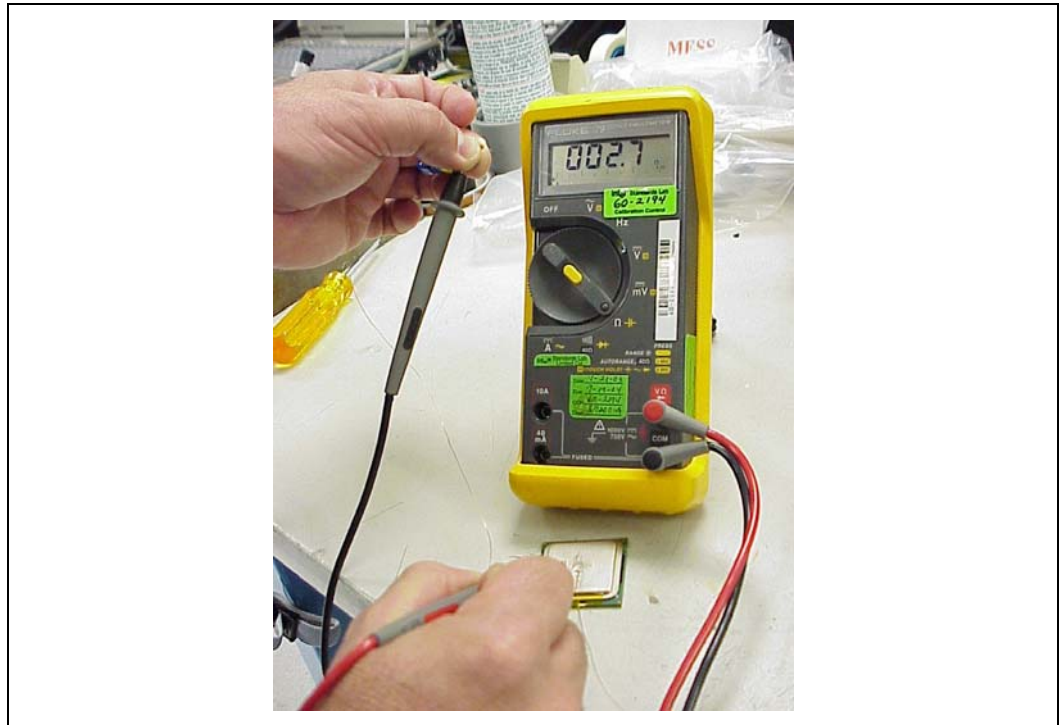
Thermocouple bead

Body of IHS

7. Place a third piece of tape at the end of the step in the groove, as shown in Figure 26. This tape will create a solder dam to prevent solder from flowing into the larger IHS groove section during the melting process.

**Figure 26. Third Tape Installation**

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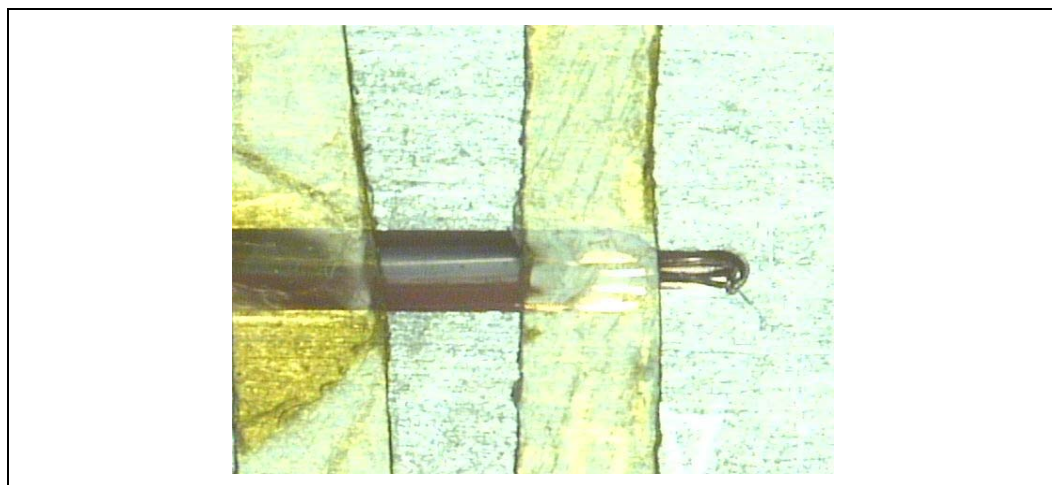
8. Measure resistance from the thermocouple end wires (hold both wires to a DMM probe) to the IHS surface (Figure 27). This should be the same value as measured during the thermocouple conditioning (Section C.5.1, step 3).

Figure 27. Measuring Resistance between Thermocouple and IHS

9. Using a fine point device, place a small amount of flux on the thermocouple bead. Be careful not to move the thermocouple bead during this step (Figure 28). Ensure the flux remains in the bead area only.

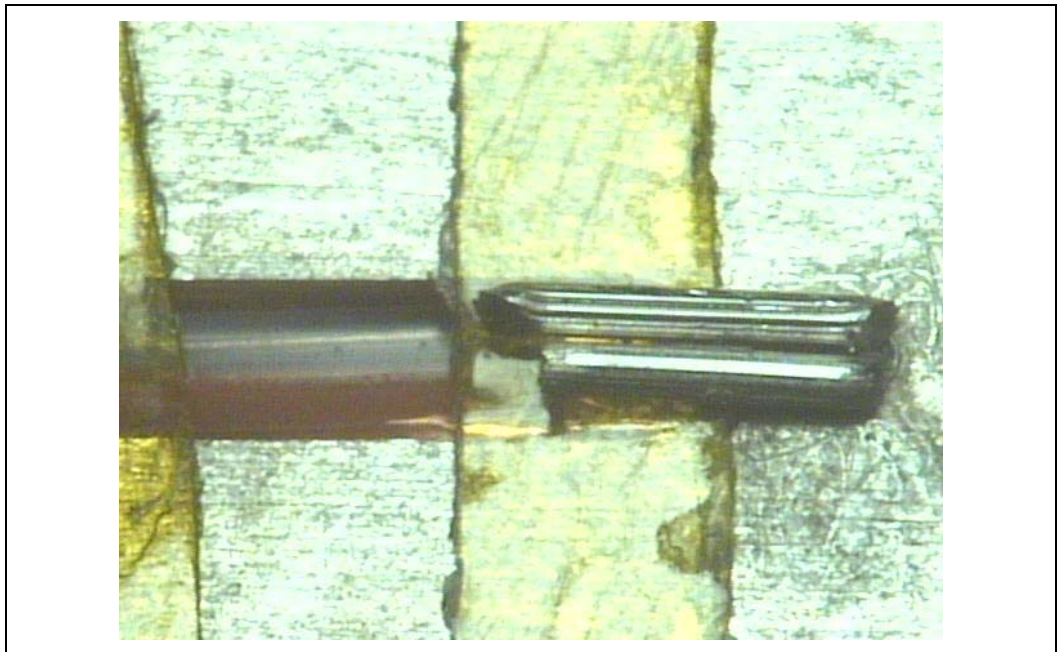**Figure 28. Applying Flux to the Thermocouple Bead**
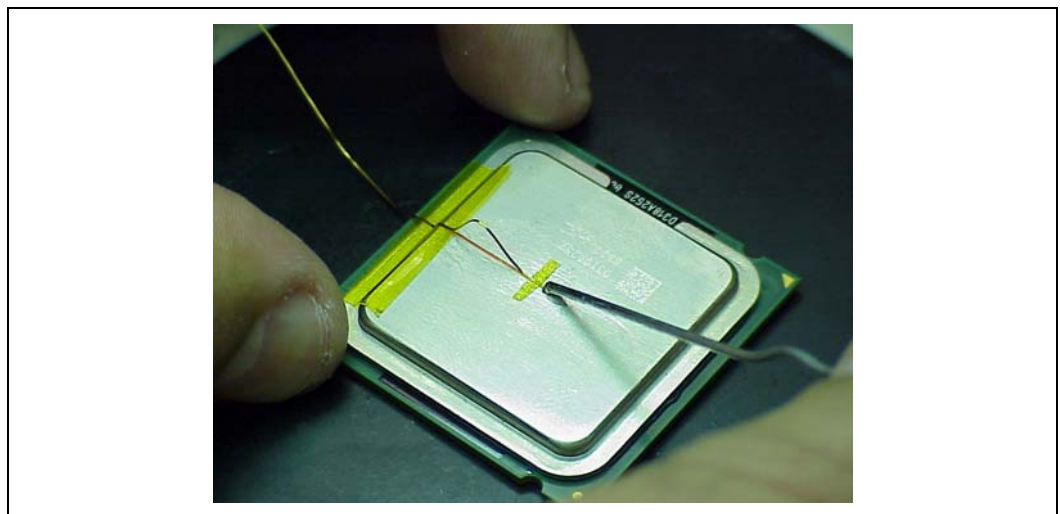
10. Cut two small 1.5 mm [1/16 inch] pieces of solder from the roll, using tweezers to hold the solder while cutting with a fine blade(Figure 29)

Figure 29. Cutting Solder

11. Place the two pieces of solder in parallel, directly over the thermocouple bead (Figure 30).

Figure 30. Positioning Solder on IHS

12. Measure the resistance from the thermocouple end wires again using the DMM (refer to section C.5.1.step 2) to ensure the bead is still properly contacting the IHS.

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C.5.3   Solder Process

1. Make sure the thermocouple that monitors the solder block temperature is positioned on the heater block. Connect the thermocouple to a hand-held meter to monitor the heater block temperature.

2. Verify the temperature of the heater block station has reached $155° C \pm 5°$ before you proceed.

3. Connect the thermocouple for the device being soldered to a second hand-held meter to monitor IHS temperature during the solder process.

Figure 31. Solder Station Setup

4. Remove the land-side protective cover and place the device to be soldered in the solder station. Make sure the thermocouple wire for the device being soldered is exiting the heater toward you.

Note: Do not touch the copper heater block at any time, as it is very hot.

5. Move a magnifying lens light close to the device in the solder status to get a better view when the solder begins to melt (Figure 32).

6. Lower the heater block onto the IHS. Monitor the device IHS temperature during this step to ensure the maximum IHS temperature is not exceeded.

Note: The target IHS temperature during reflow is $150° C \pm 3°$. At no time should the IHS temperature exceed $155° C$ during the solder process, as damage to the device may occur.

7. You may need to move the solder back toward the groove as the IHS begins to heat. Use a fine tip tweezers to push the solder into the end of the groove until a solder ball is built up.

Figure 32. View through Lens at Solder Station

8. Lift the heater block and magnifying lens, and using tweezers, quickly rotate the device 90 degrees clockwise. Using the back of the tweezers, press down on the solder and drag the tweezers gently away from the groove side of the HIS (see Figure 33). This will force out the excess solder.

Figure 33. Removing Excess Solder
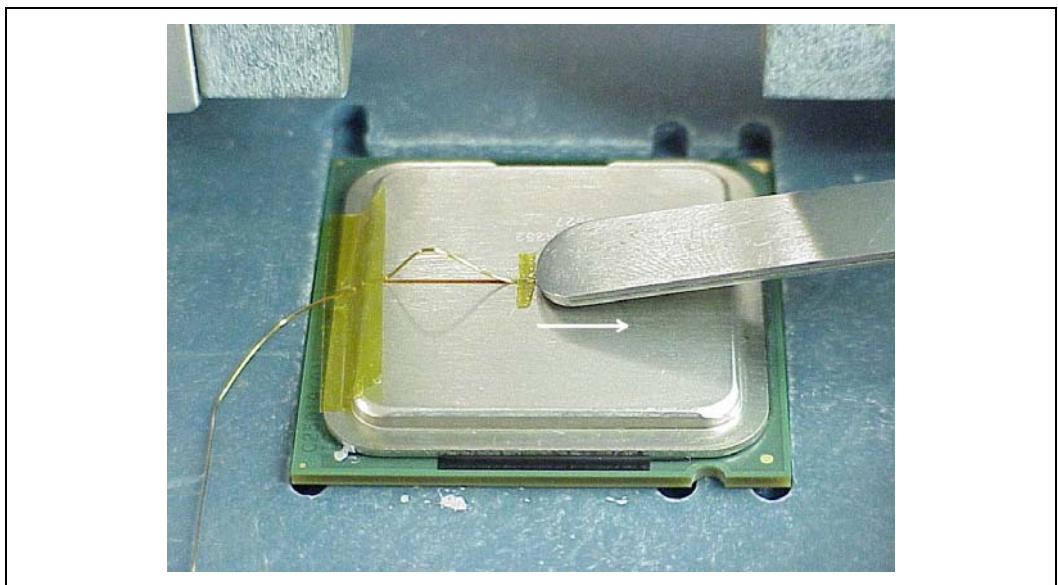
9. Allow the device to cool down. Blowing compressed air on the device can accelerate the cooling time. Monitor the device IHS temperature with a hand-held meter until it drops below 50° C before moving it to the microscope for the final steps.

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C.5.4   Cleaning and Completion of Thermocouple Installation

1. Remove the device from the solder station and continue to monitor TTV IHS temperature with a hand-held meter. Place the device under the microscope and remove the three pieces of Kapton tape with tweezers, keeping the longest for re-use.

2. Straighten the wire and work the wire into the groove. Bend the thermocouple over the edge of the IHS. Secure it at the edge of the IHS with the long piece of Kapton tape, as shown in Figure 34.
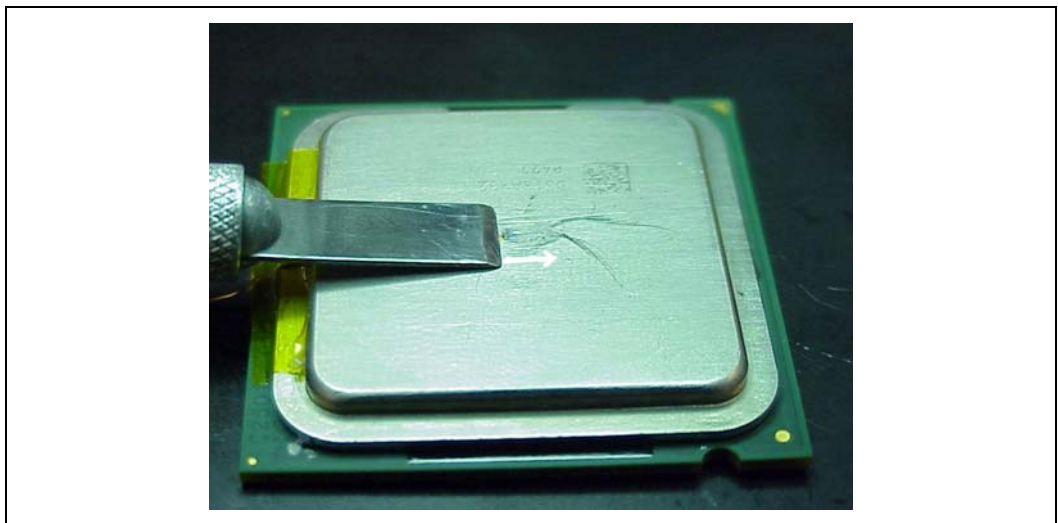
Note: The wire must be straight so it does not sit above the IHS surface at any time.

Figure 34. Thermocouple Placed into Groove

3. Using a blade, carefully shave the excess solder above the IHS surface. Only shave in one direction until solder is flush with the groove surface (Figure 35).

Figure 35. Removing Excess Solder

Note: Take usual precautions when using open blades.

4. Clean the surface of the IHS with alcohol and use compressed air to remove any remaining contaminants.

5. Fill the rest of the groove with Loctite 498 adhesive. Verify under the microscope that the thermocouple wire is below the surface along the entire length of the IHS groove (Figure 36).

Figure 36. Filling Groove with Adhesive

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6. To speed up the curing process, apply Loctite accelerant on top of the adhesive and let it set for a couple of minutes (Figure 37).
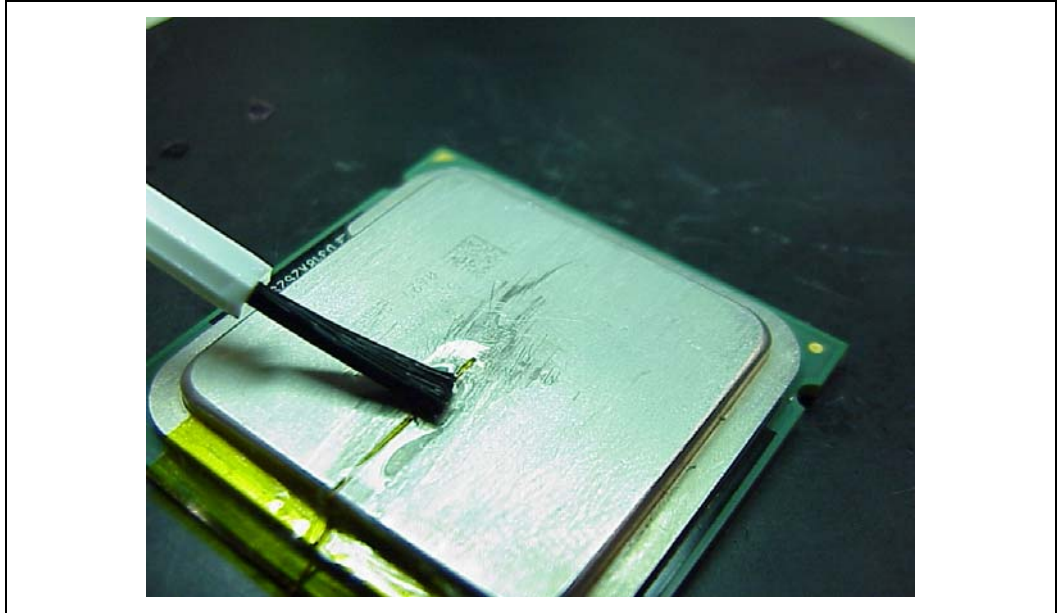
Figure 37. Application of Accelerant

Figure 38. Removing Excess Adhesive from IHS

7. Using a blade, carefully shave any adhesive that is above the IHS surface (Figure 38). The preferred method is to shave from the edge to the center of the IHS.

Note: The adhesive shaving step should be performed while the adhesive is partially cured, but still soft. This will help to keep the adhesive surface flat and smooth with no pits or voids. If there are voids in the adhesive, refill the voids with adhesive and shave a second time.

8. Clean IHS surface with alcohol and wipe.
9. Clean the LGA pads with alcohol and wipe.

10. Replace the land-side cover on the device.
11. Perform a final continuity test.
12. Wind the thermocouple wire into loops and secure, or onto the plastic roll if provided by the vendor back (Figure 39).

Figure 39. Finished Thermocouple Installation

13. Place the device in a tray or bag until it is ready to be used for thermal testing.

C.6   Thermocouple Wire Management

When installing the processor into the socket, make sure the thermocouple wires exit above the load plate as shown in Figure 40 below. Pinching the thermocouple wires between the load plate and the IHS will likely damage the wires.

Note: When thermocouple wires are damaged, the resulting reading maybe wrong. For example, if there are any cuts in the insulation where the wires are pinched between the IHS and the load plate, the thermocouple wires may make contact at this location. In that case, the temperature measured would be from the edge of the IHS/socket load plate area. This temperature is usually much lower than the temperature at the center of the IHS.

Prior to installing the heat sink, make sure that the thermocouple wires remain below the IHS top surface by running a flat blade on top of the IHS.

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Figure 40. Thermocouple Wire Management
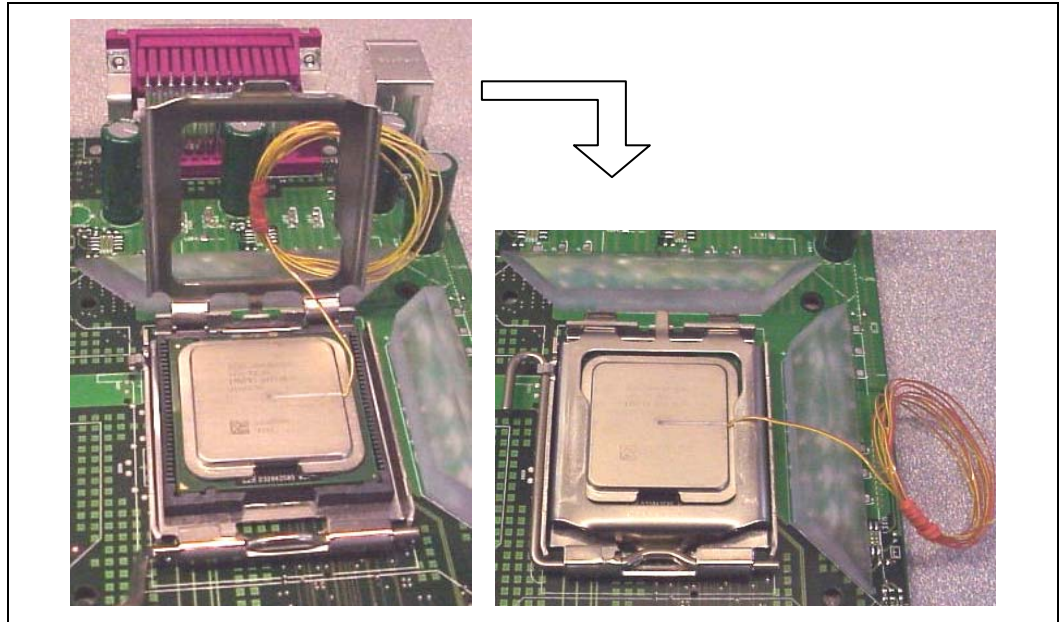
Appendix D: Validation of System Thermal Solution

This section provides system-level validation information for an active fan thermal solution that monitors the on-die thermal diode. It is assumed the system integrator has already validated that the thermal solution meets the thermal profile using the TTV, as described in Section 3.

The functional validation needs to account for the entire operating environment of the system. In addition, fan speed control implementation must be verified. The system engineer will need to account for the following factors:

- System ambient temperature range

- Interaction of internal heat loads such as hard drives, optical drives, PCI, PCI Express, graphics, etc.

- Thermal Profile specification for components at end of life, not beginning of life

- Variations in heat sink and thermal interface material

- Calibration of equipment

D.1   Processor Power Dissipation

Each processor is calibrated at the factory with a $T_{CONTROL}$ value. That value is determined in large part by the leakage power. A processor with a higher $T_{CONTROL}$ will inherently dissipate more power than a part with a low $T_{CONTROL}$ when running the same application workload.

Each processor will have characteristic maximum power dissipation. The characteristic maximum power dissipation is defined at the TDP workload percentage. To determine the maximum characteristic power for a specific processor, run the maxpower program at the TDP workload percentage and near $T_{CASE-MAX}$. At the time of publication, the recommended TDP workload percentage for the Intel® Pentium® 4 Processor 651 with Hyper-Threading Technology† is 80 percent. Intel continues to evaluate this value and may make changes in the future.

The characteristic power dissipation of any randomly selected processor is unlikely to be equal to the TDP power as listed in the Datasheet. The TDP power may be approached by running the maxpower program at greater than TDP workload. When operating greater than TDP workload, there is a risk that the PROCHOT# signal or even THERMTRIP# signal may go active and invalidate the test.

D.2   Preparation

Follow the electrical load line characterization procedure for the board(s) that will be used in the system thermal test. An accurate load line is necessary to determine the power dissipated during the test. The power dissipated can then be plotted on the thermal profile to determine compliance to the maximum case temperature.

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Install thermocouples on selected functional processors as described in Appendix C:. It is beneficial but not required to test with processors having different $T_{CONTROL}$ values. Selecting a pair of processors with a high and low $T_{CONTROL}$ value can help confirm compliance to thermal and acoustic requirements over a range of $T_{CONTROL}$ values.

D.3   System Setup

Instrument the system to capture the following data:

- Processor case temperature
- Processor on-die thermal diode temperature
- Heat sink local ambient temperature
- Processor power
- PROCHOT# signal
- Fan speed to estimate acoustic signature with dBA vs. RPM curves (optional)
- Other points of interest for overall system validation

The data collection process should sample all parameters at least once per second. Reading the on-die thermal diode more frequently is encouraged, as the rate of change for the thermal diode can be up to 50° C per second.

D.4   System Test Conditions

The system integrator should select system thermal loads and ambient temperatures that are consistent with end-use conditions of the system under test. The choice of active or passive system loads is up to the system integrator. The processor can be exercised with the maxpower program or other suitable high power applications. Example load scenarios for thermal / acoustic validation are given in Table 5. The conditions outlined here may differ from your own system requirements.

Table 5 Example System Test Conditions

Condition	Ambient (°C) (External)	Power
Minimum Loading for Acoustic Verification	25	Windows* XP Idle
Typical Operation Load and Environment	25	User Defined
Maximum Operating Load and Environment	35	80%

D.5   Pass / Fail Criteria

The data logs should be checked to identify the test conditions where T_{DIODE} exceeds $T_{CONTROL}$. To determine pass/fail, the power dissipation must be plotted on the thermal profile to get the maximum allowed case temperature. If the measured case temperature is less than the maximum case temperature from the thermal profile at that power dissipation, the test is successful. By design, the thermal solution fan should be at 100% of the fan operating speed for the ambient temperature being examined when T_{DIODE} exceeds $T_{CONTROL}$.

If PROCHOT# goes active during any validation run, that test should be considered a failure. When PROCHOT# is active, Thermal Monitor will take steps to reduce the processor power (see Section 4 for details). The system integrator should carefully review the test data to determine the conditions that led to the activation of Thermal Monitor.

For all other conditions where T_{DIODE} is less than $T_{CONTROL}$, the thermal solution is providing sufficient cooling to meet the processor thermal specification.

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Appendix E: Mechanical Drawings

The following table lists the mechanical drawings included in this appendix. These drawings refer to the reference thermal mechanical enabling components for the processor.

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

Drawing Description	Page Number
1U Heat Sink for Intel® Pentium® 4 Processor 651 with HT Technology† for Embedded Applications	74
2U Heat Sink for Intel® Pentium® 4 Processor 651 with HT Technology† for Embedded Applications	75
1U/2U Motherboard Keep-out and Height Restrictions, Primary Side	76
1U/2U Motherboard Keep-out, Secondary Side	77

Figure 41. 1U Heat Sink for Intel® Pentium® 4 Processor 651 with HT Technology† for Embedded Applications
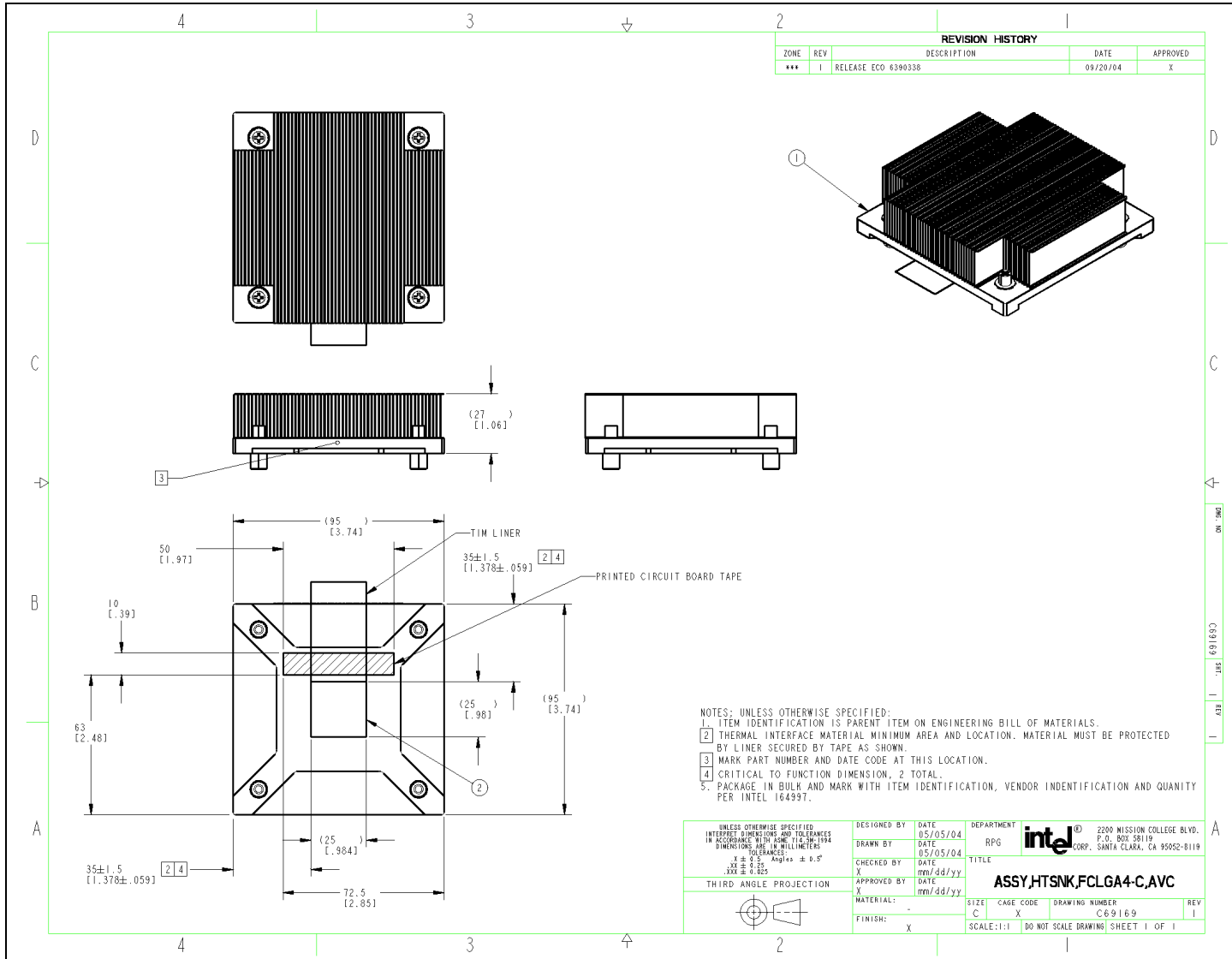
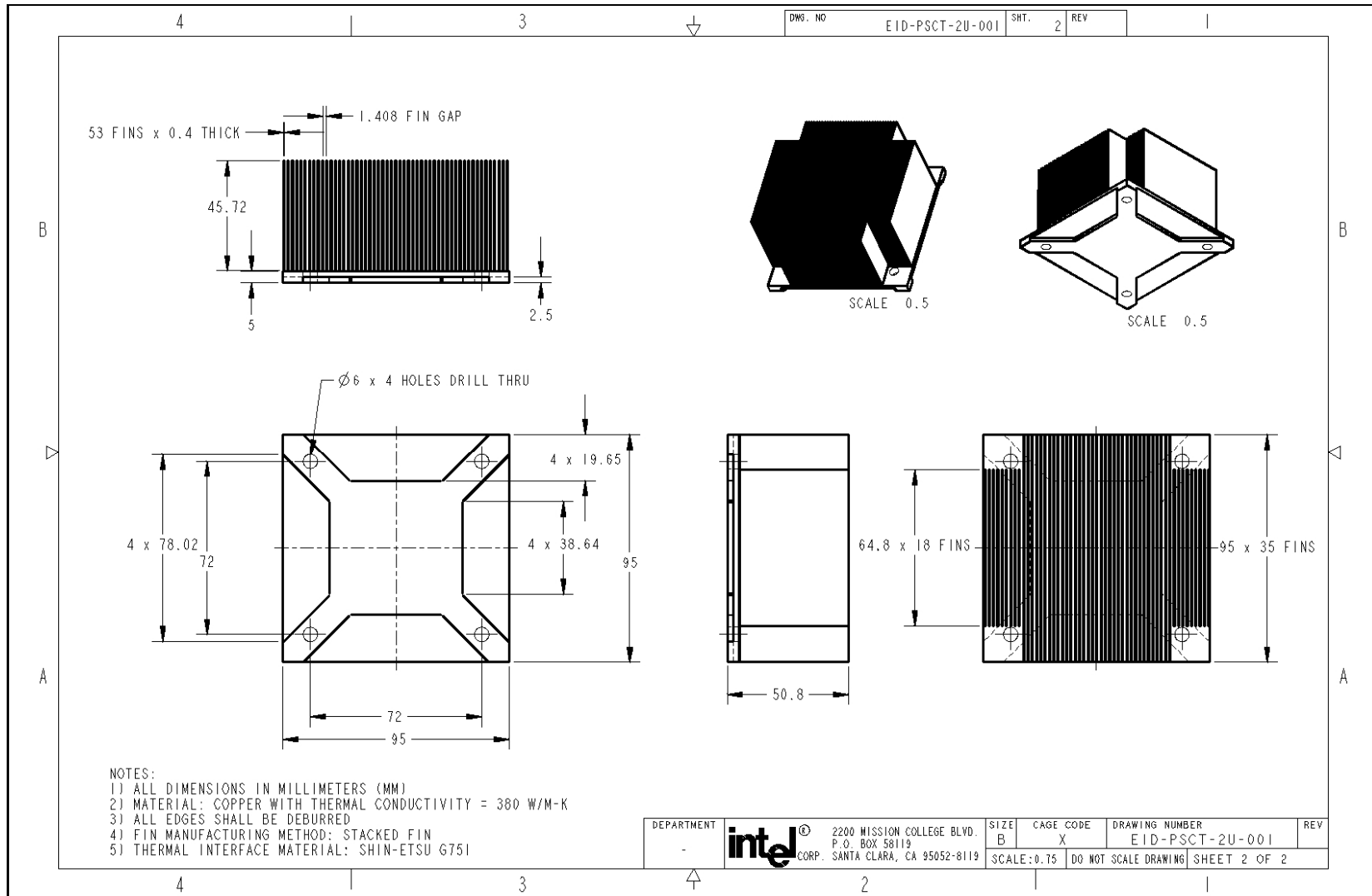**Figure 42. 2U Heat Sink for Intel® Pentium® 4 Processor 651 with HT Technology† for Embedded Applications**

Figure 43. 1U/2U Motherboard Keep-out and Height Restrictions, Primary Side

Intel® Pentium® 4 Processor 651 with HT Technology for Embedded Applications
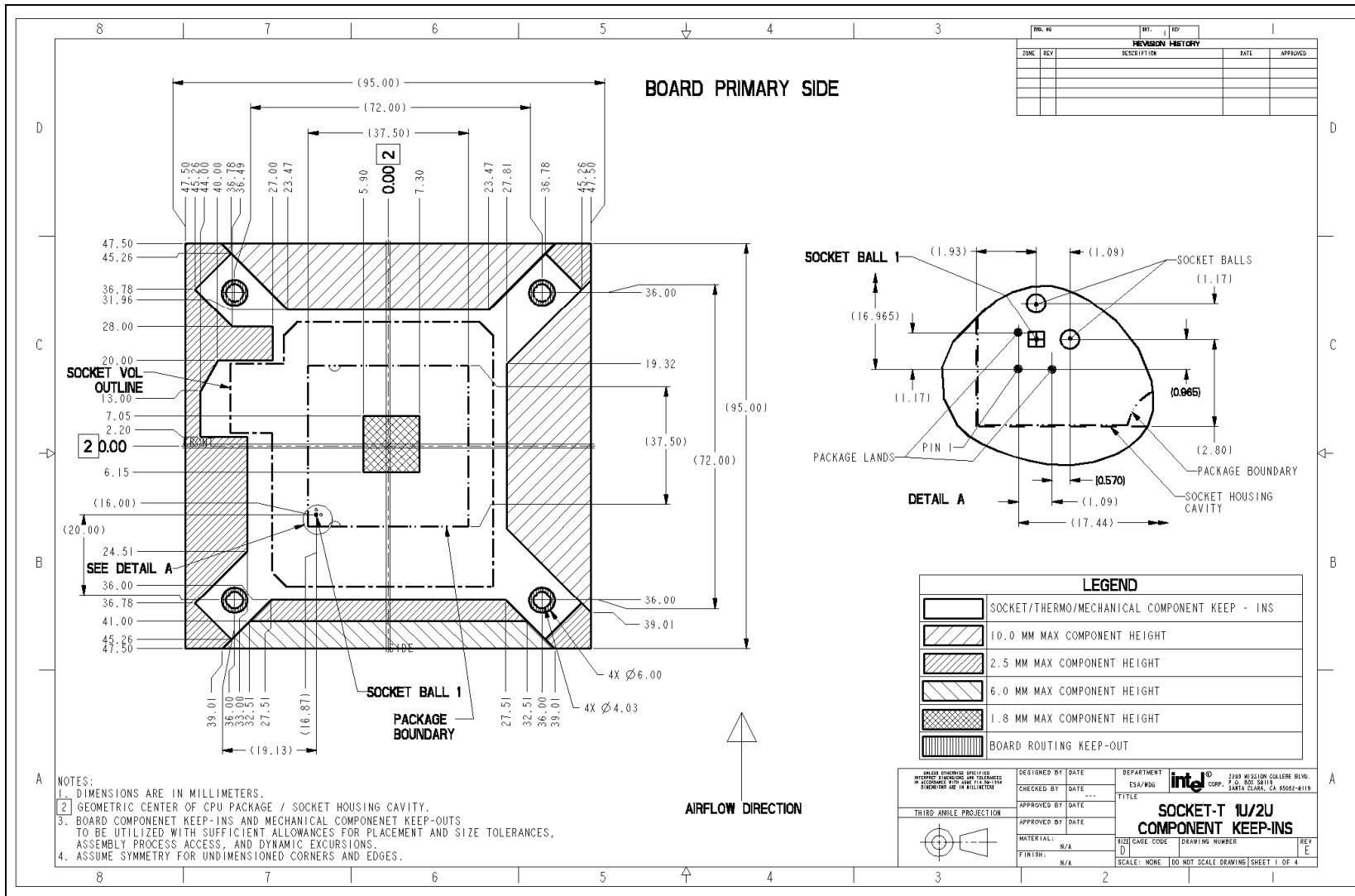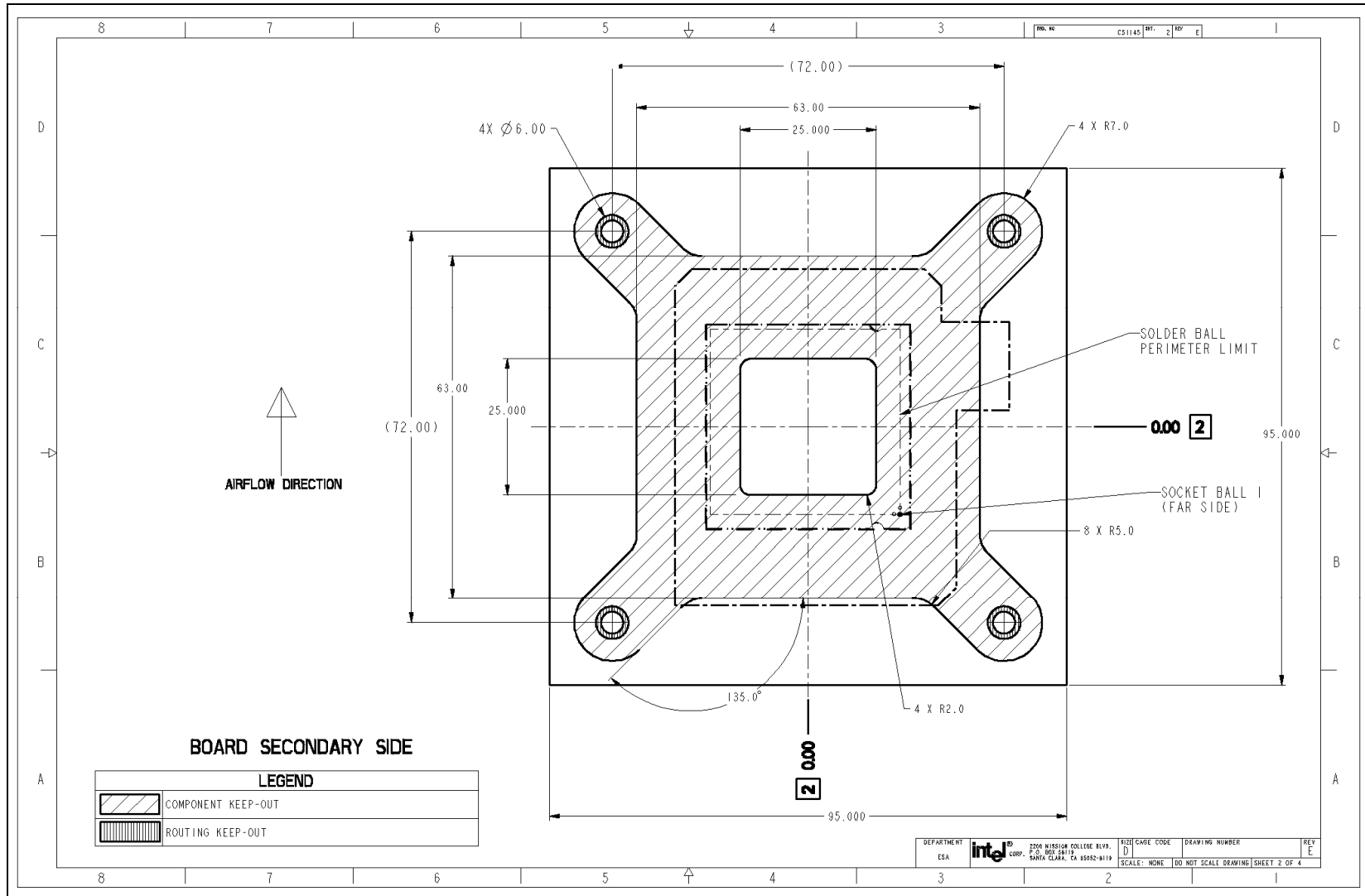**Thermal Design Guidelines**

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Figure 44. 1U/2U Motherboard Keep-out, Secondary Side

Appendix F: Intel Enabled Reference Solution Information

This appendix includes supplier information for Intel enabled vendors for the 1U and 2U thermal solutions.

Table 6 lists suppliers that produce Intel enabled reference components. The part numbers listed below identify these reference components. End users are responsible for verification of the Intel enabled component offerings with the supplier. OEMs and system integrators are responsible for thermal, mechanical, and environmental validation of these solutions.

Table 6. Intel Reference Component 1U and 2U Thermal Solution Providers

Supplier	Part	Part #	Contact	Phone	Email
AVC* (ASIA Vital Components* Co., Ltd)	1U Heat Sink	C69169-001	David Chao	+886-2-22996930 extension: 619	david_chao@avc.com.tw
CoolerMaster*	2U Heat Sink	EID-PSCT-2U-001	Wendy Lin	510-770-0855	wendy@coolermaster.com

Note: These vendors and devices are listed by Intel as a convenience to Intel's general customer base, but Intel does not make any representations or warranties whatsoever regarding quality, reliability, functionality, or compatibility of these devices. This list and/or these devices may be subject to change without notice.

Cedar Mill Processor for Embedded Applications
Thermal Design Guidelines