ULV Intel® Celeron® M Processor at 600 MHz for Fanless Set Top Box Applications

Thermal Design Guide

April 2005

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Revision History

Date	Revision	Reference #	Description
April, 2005	1.0	D18741-001	First release.

1 Introduction

This document provides thermal design guidelines for the Ultra Low Voltage Intel® Celeron® M processor at 600 MHz for set top box applications in the micro-Flip Chip Ball Grid Array (micro-FCBGA) package. Detailed mechanical and thermal specifications for this processor can be found in the *ULV Intel Celeron M Processor Datasheet*. This design guide specifically outlines recommendations and reference designs for natural convection (fanless) thermal solutions.

The information provided in this document is for reference only and additional validation must be performed prior to implementing the thermal designs into final production. The intent of this document is to assist OEMs with the development of thermal solutions for their individual designs. The final thermal solution, including the heat sink, attachment method, and thermal interface material (TIM) must comply with the mechanical design, environmental, and reliability requirements delineated in the *ULV Intel Celeron M Processor Datasheet*. It is the responsibility of each OEM to validate the thermal solution design with their specific applications.

1.1 Document Goals

This document describes the thermal characteristics of the ULV Intel Celeron M processor at 600 MHz and provides guidelines for meeting the thermal requirements imposed on a single-processor system. The reference thermal solutions presented in this document are specifically designed for natural convection, applied computing applications in typical set top box form factors.

1.2 Document Scope

This document discusses the thermal management techniques for the ULV Intel Celeron M processor at 600 MHz, specifically in fanless set top box applications. The physical dimensions and power numbers used in this document are for reference only. Please refer to the processor datasheet for the product dimensions, thermal design power, and maximum junction temperature. In case of conflict the data in the datasheet supersedes any data in this document.

1.3 Related Documents

Table 1. Document References

Title	Number	Location
Intel Celeron M Processor Datasheet, Rev. 2.0	300302	http://developer.intel.com/
Ultra Low Voltage Intel Celeron M Processor at 600 MHz Datasheet, Rev. 2.0	301753	http://developer.intel.com/
Intel® Pentium® M Processor and Intel Celeron M Processor for Embedded Applications, Thermal Design Guide, Rev 2.0	273885	http://developer.intel.com/
ULV Intel Celeron M Processor at 600 MHz for Embedded Applications, Thermal Design Guide, Rev 1.0	302288	http://developer.intel.com/
Thermal Considerations for Passive Set Top Box Design Guide, Rev 1.0	17114	See your local Intel field representative

1.4 Definitions of Terms

Table 2. Definitions of Terms

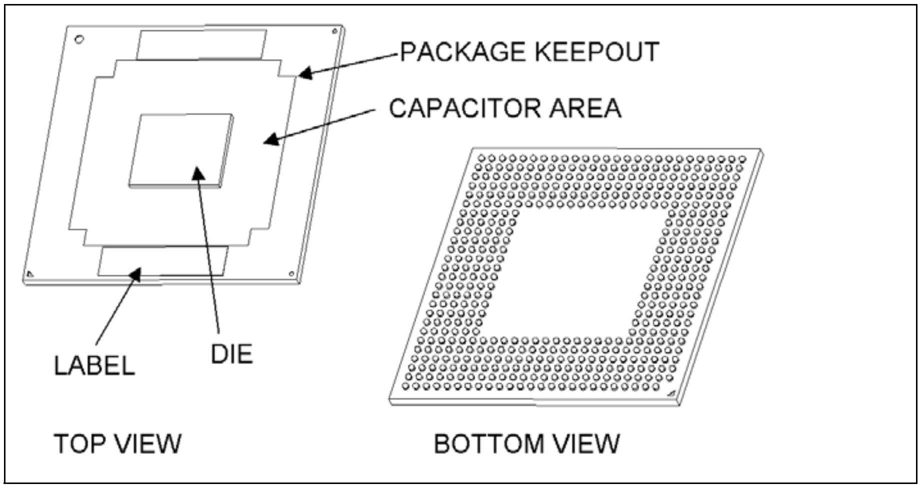
Term	Definition
CFM	Cubic Feet per Minute
LFM	Linear Feet per Minute
Natural Convection Cooling (free convection)	The transferring of heat from a surface to a fluid (i.e., air or liquid) where the convection flow is generated only by fluid buoyancy. No airflow devices (i.e., fans) are used in the system.
PCB	Printed Circuit Board
Thermal Interface Material (TIM)	The thermally conductive compound between the heat sink and processor die. This material fills air gaps and voids, and improves the transfer of heat from the die to the heat sink.
Thermal Design Power (TDP)	A design point for the processor. OEMs must design thermal solutions that meet TDP and $T_{junction}$ specifications as specified in the processor's datasheet.
$T_{junction}$, T_j	The maximum junction temperature of the processor, as measured or specified in the processor datasheet.
T_{case}, T_c	The temperature at the geometric center of the top surface of the package. For bare die package, this is the temperature at the center of the back surface of the die.
T_{sink}, T_s	The temperature of the heat sink base plate at the center location of the package or die.
T_{amb}	The ambient temperature locally surrounding the processor. The ambient temperature should be measured approximately one inch (25.4 mm) upstream of a passive heat sink or at the fan inlet of an active heat sink.
T_{amb_max}	Maximum allowable T_{amb} that can be supported by a thermal solution.
T_{air}	The air temperature external to the chassis enclosure. Also, referred to as the external ambient temperature, or the chassis ambient temperature.
T_{rise}	The temperature rise of the air as it enters from the chassis till it reaches the region of the processor: defined as (T_{amb} - T_{air})
Ψ_{ja}	The thermal resistance between the processor's junction and the ambient air. A measure of global thermal performance of a component thermal solution module using total package thermal design power: (T_j - T_{amb})/TDP.
Ψ_{jc} , $\Psi_{package}$	The thermal resistance between the processor's junction and the package case. Also represents the package resistance. A measure of package thermal performance using total package thermal design power: (T_j – T_c)/TDP.
Ψ_{cs} , Ψ_{TIM}	The case to sink thermal resistance, which is dependent on the thermal interface material (TIM). Also referred to as Ψ_{TIM}. A measure of TIM thermal performance using total package thermal design power: (T_c – T_s)/TDP.
Ψ_{sa} , $\Psi_{heatsink}$	The sink-to-ambient thermal resistance. A measure of heat sink thermal performance using total package thermal design power : (T_s – T_{amb})/TDP.

2 Mechanical Guidelines

2.1 Processor Package

The ULV Intel Celeron M processor at 600 MHz with 400-MHz Front side bus is available in the 479-ball micro-Flip Chip Ball Grid package technology. Detailed mechanical information including package dimensions can be found in the processor datasheet. Figure 1 shows a basic representation of the micro-FCBGA package.

Figure 1. Top and Bottom Isometric Views of the Micro-FCBGA Package

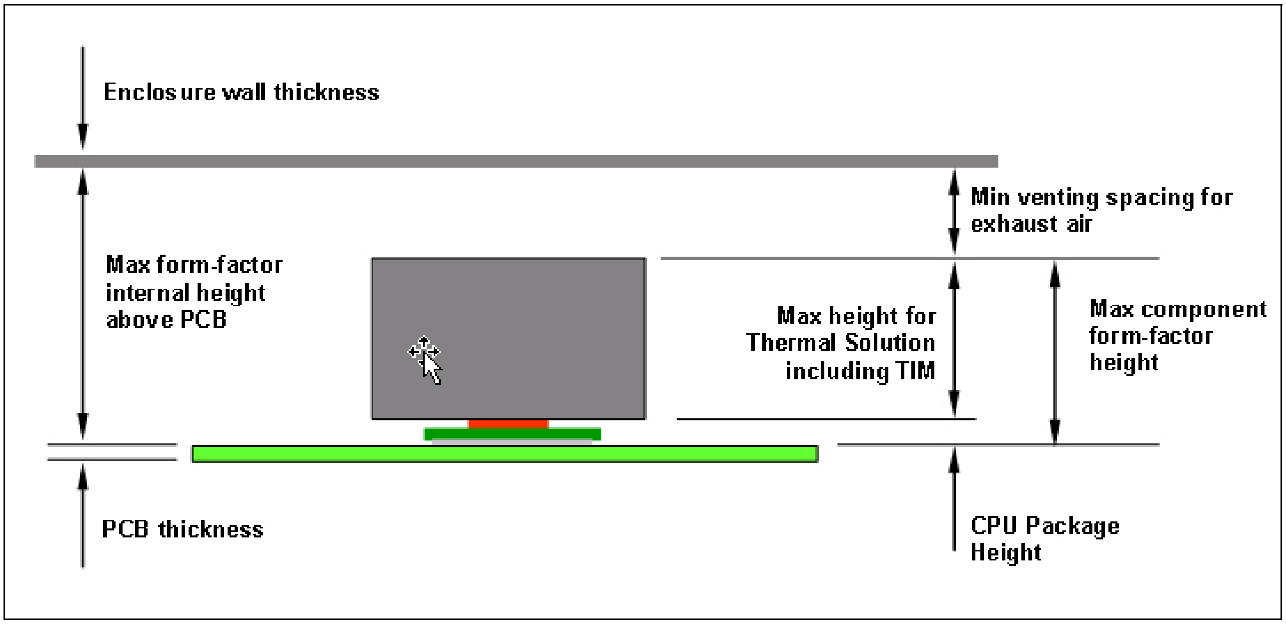


2.2 Thermal Solution Volumetric Constraint Zones

The reference thermal solutions enabled for the ULV Intel Celeron M processor at 600 MHz may have volumetric constraint zones that will allow for the thermal solution to be assembled to a system board. System designers must take these zones into account so that the thermal solution will be properly assembled to the board and not interfere with any other components. The volumetric constraint zones for the reference natural convection thermal solutions are shown in Appendix A "Mechanical Drawings". These zones are specific to the natural convection solutions typical set-top-box form factors. Additional volumetric constraints for forced convection thermal solutions are delineated in the *Intel Pentium M Processor and Intel Celeron M Processor for Embedded Applications Thermal Design Guide*.

The maximum allowable height for a thermal solution is very important in the overall thermal performance and is a factor in the volumetric constraint for a thermal solution. This height is determined by the form factor in which the computer system is placed. For the Intel® reference thermal solutions, the maximum allowable height was based on the ATX, mini-ATX and micro-ATX form factor requirements. These solutions may apply for other form factors, but it is up to the system integrator to ensure that all thermal and mechanical requirements are validated in the final intended configuration. Figure 2 shows a generic mechanical stack-up for the ULV Intel Celeron M processor and the geometric parameters that need to be accounted for when determining the maximum allowable height for a thermal solution.

Figure 2. Typical Mechanical Stack-up



3 Thermal Guidelines

The overall performance requirement of a component thermal solution depends on the following three parameters:

- Thermal Design Power (TDP)
- Maximum junction temperature (T_j)
- Operating ambient temperature (T_{amb})

The guidelines and recommendations presented in this document are based on specific parameters that are relevant to designing a natural convection thermal solution. The overall heat dissipation capability of a thermal solution depends on many parameters, including:

- Package thermal performance or resistance (Ψ_{jc}, $\Psi_{package}$)
- Thermal performance or resistance of Thermal Interface Material, TIM (Ψ_{cs}, Ψ_{TIM})
- Heat sink thermal performance or resistance (Ψ_{ca}, $\Psi_{heatsink}$)
- Maximum junction temperature, as specified in the datasheet (T_j)
- Operating ambient temperature local to the component (T_{amb})

To develop a reliable thermal solution all of the appropriate variables must be considered. Thermal simulations and characterizations must be performed. The example solutions presented in this document must be validated in their final intended system.

3.1 Heat Sink Design Considerations

There are three fundamental modes of heat transfer to be considered:

1. The conduction 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 improve the heat sink performance. The cross-sectional area, 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 die and the heat sink base has a greater impact on the overall thermal solution performance as processor cooling requirements become more difficult to satisfy. Thermal Interface Material (TIM) is used to fill in the gap between the die and the bottom surface of the heat sink which would have been filled otherwise with a layer of air and microscopic voids. High performance TIMs with good surface wetting characteristics will thereby improve the overall performance of the stack-up (die-TIM-heat sink). With poor heat sink interface flatness and/or roughness, TIM may not adequately fill the gap. The TIM thermal performance depends on its thermal conductivity, surface wetting characteristics, and the pressure applied to it.
2. The convection from the exposed surfaces to the air stream. After conduction carries the heat from the heat source to the surfaces exposed to air flow, such as the surface of the heat sink fins, the heat is dissipated from the heat sink by means of either convection or radiation heat transfer. Convection heat transfer occurs to the airflow from the surfaces exposed to the flow. Convection heat transfer is characterized by the temperature difference between the exposed surface and the local ambient air, and the total area of the exposed surfaces. A thermal solution with a greater temperature difference and larger exposed area will have better cooling capability. In convection, the faster the air velocity over the surface and cooler the air, the more efficient the resulting cooling. In the case of natural convection with no externally driven induced or forced airflow, the convection flow is created by the upward buoyancy force acting on the heated hot air, and its velocity depends on the surface geometry and the surface-to-air temperature difference.
3. The radiation from the component to surrounding surfaces. Radiation heat transfer takes place between any two surfaces facing each other and having different temperatures. In a fanless system, the amount of radiation from a hot component like the CPU to the cooler surrounding surfaces like the interior wall of the chassis enclosure can be a significant portion of the overall heat sink thermal dissipation. It is strongly recommended that the chassis layout designer to take advantage of this naturally existing heat dissipation mechanism by comprehending the radiation phenomenon and promoting this radiation heat transfer. A bare aluminum heat sink can be simply anodized or painted to improve the radiation characteristics of the heat sink surface, resulting in a substantial thermal performance improvement.

3.1.1 Heat Sink Size

The size of the heat sink is dictated by height restrictions in a system and by the foot-print area available on the motherboard. The height of the heat sink must comply with the requirements and recommendations published for the motherboard form factor of interest.

3.1.2 Heat Sink Weight

With the need to push air cooling toward better performance, heat sink solutions tend to grow larger, resulting in increased weight. The insertion of highly thermally conductive materials like copper to increase heat sink thermal conduction performance results in even heavier solutions. The heat sink weight must take into consideration the package and socket load limits, the mechanical capability of the heat sink retention mechanism, and the mechanical shock and vibration profile targets.

3.1.3 Thermal Interface Material

A thermal interface material between the processor die and the heat sink base is generally required to improve thermal conduction from the die 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 during final assembly.

All thermal interface materials should be sized and positioned on the heat sink base in a way that ensures the entire processor die 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 cover over it prior to shipping. This cover must be removed prior to heat sink installation.

3.2 Natural Convection Cooling Considerations

Many factors play an important role in the ability to design a natural convection thermal solution that will keep the processor within its maximum operating temperature. Both processor attributes (i.e., $T_{junction}$, TDP, etc.) and the system attributes need to be considered. These include:

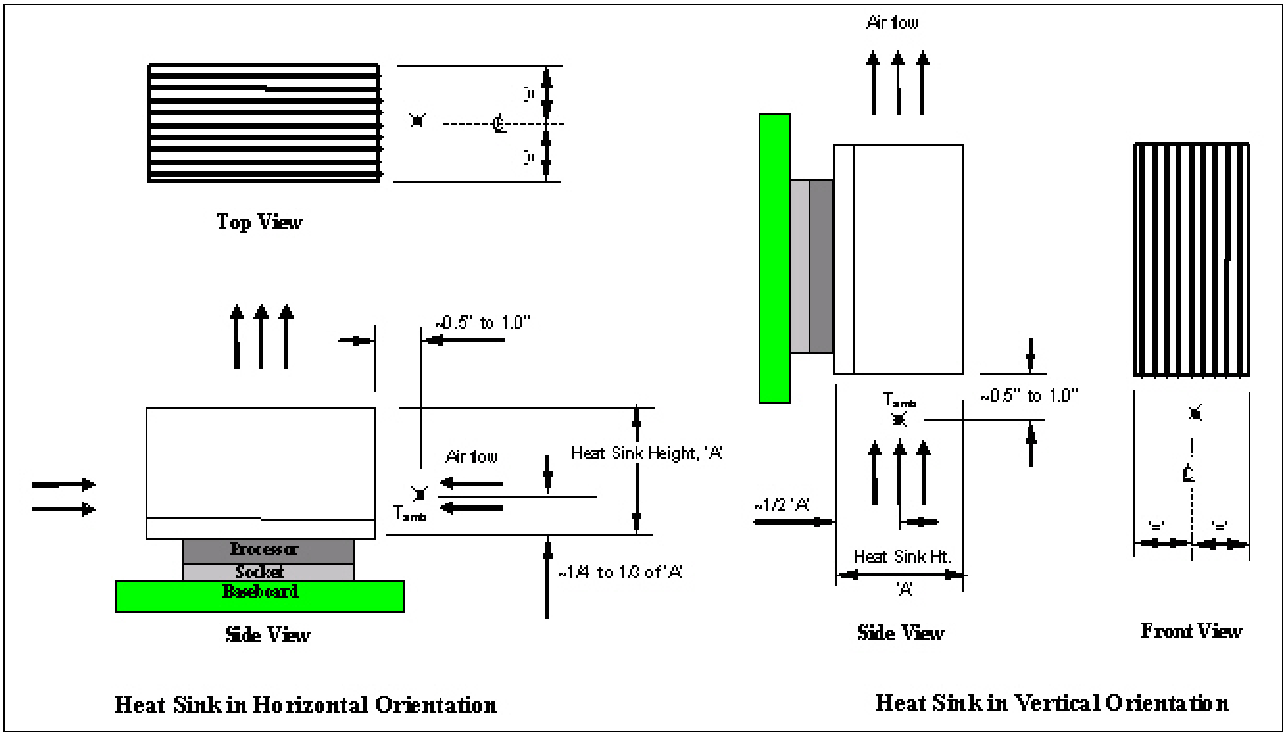
- Operating local ambient temperature (T_{amb})
- Heat-generating component placement and system orientation
- Location and size of venting
- Available volume for thermal solution

It is very challenging to design one thermal solution that will apply for multiple form factors. Thermal modeling and analysis needs to be performed in order to optimize the thermal solution for the intended form factor and environment. This in essence makes most natural convection thermal solutions custom designs.

3.2.1 Local Ambient Temperature (T_{amb})

The local ambient temperature (T_{amb}) has a significant influence when developing a thermal solution. The T_{amb} is defined as the local temperature at the location approximately one half to one inch upstream of the thermal solution. For a natural convection system, the relative location of the thermocouple for measuring T_{amb} to the heat sink depends on the orientation of the heat sink with respect to the local geometry. This location should be chosen so that the measured temperature represents the temperature of the incoming air toward the heat sink and is not affected by the air that is exhausting away from the heat sink. In a horizontal configuration, the measurement should be taken at the sides of the heat sink. In vertical orientation, the measurement should be taken about below the leading edge. The local ambient temperature represents the external air temperature outside the enclosure plus any temperature rise due to other components in the system: ($T_{amb} = T_{air} + T_{rise}$). The recommended measurement locations for T_{amb} are shown in Figure 3.

Figure 3. Local Ambient Temperature Locations for Passive Heat Sink



3.2.2 Thermal Resistance of a Heat Sink

The thermal characterization parameter or Ψ (Psi) is calculated for a given thermal system so that it may be compared to other thermal systems. In any computer system it is necessary to calculate the required thermal characterization parameter needed in order to keep the processor within its operating temperatures. The thermal solution must maintain the processor die at or below the specified junction temperature. The equation for calculating the junction-to-ambient thermal characterization parameter is shown below.

$$\psi_{ja} = \frac{T_j - T_{amb}}{TDP} \tag{1}$$

where:

Ψ_{ja} = junction-to-ambient thermal resistance in °C/W

T_j = maximum junction temperature of processor as specified in the datasheet in °C

T_{amb} = local ambient air temperature in °C (= $T_{air} + T_{rise}$)

TDP = Thermal Design Power in W

When calculating the required Ψ, it is important to determine the allowable temperature rise from the maximum operating environment to the component's maximum specification. It is important to know that lower Ψ_{ja} values require better thermal solutions and vice versa.

Typical T_{amb} values for natural convection systems depend linearly on T_{rise} which in turn depends largely on specific chassis design and the relative location of the component of interest with respect to other heat generating components within the system. For typical set top box chasses with good venting designs incorporated at thermally critical locations, this rise ranges from approximately 10 to 20°C. Considering a typical value for the external air temperature in set-top-box applications at T_{air} = 35-45°C, T_{amb} may become as high as 60-65°C. In some worst cases with thermally challenging circumstances, such as a compact small form-factor box placed in a confined or enclosed environment, it may be necessary to anticipate T_{amb} value of as high as 70°C. As an example, the thermal solution needed to cool an Intel® processor with a T_j of 100 °C and a TDP of 7.0 W in a system with a T_{amb} = 70 °C, would need to have a junction-to-ambient thermal resistance of:

$$\Psi_{ja} = \frac{100^{o}C - 70^{o}C}{7W} = 4.29^{o}C/W \tag{2}$$

The above case requires a thermal solution with a thermal characterization parameter less than or equal to 4.29°C/W to keep the component temperatures at or below the specifications.

Figure 4 shows the relative difficulty and limitations to design a natural convection solution for the ULV Intel Celeron M processor at 600 MHz. Figure 5, which is essentially a graphical version of Figure 4, shows the thermal solution requirements for the ULV Intel Celeron M processor at 600 MHz at TDP = 7.0W as a function of increasing T_{amb}.

Note: Note that as the T_{amb} increases, a better Thermal Solution is needed (e.g., Ψ_{ja} must decrease).

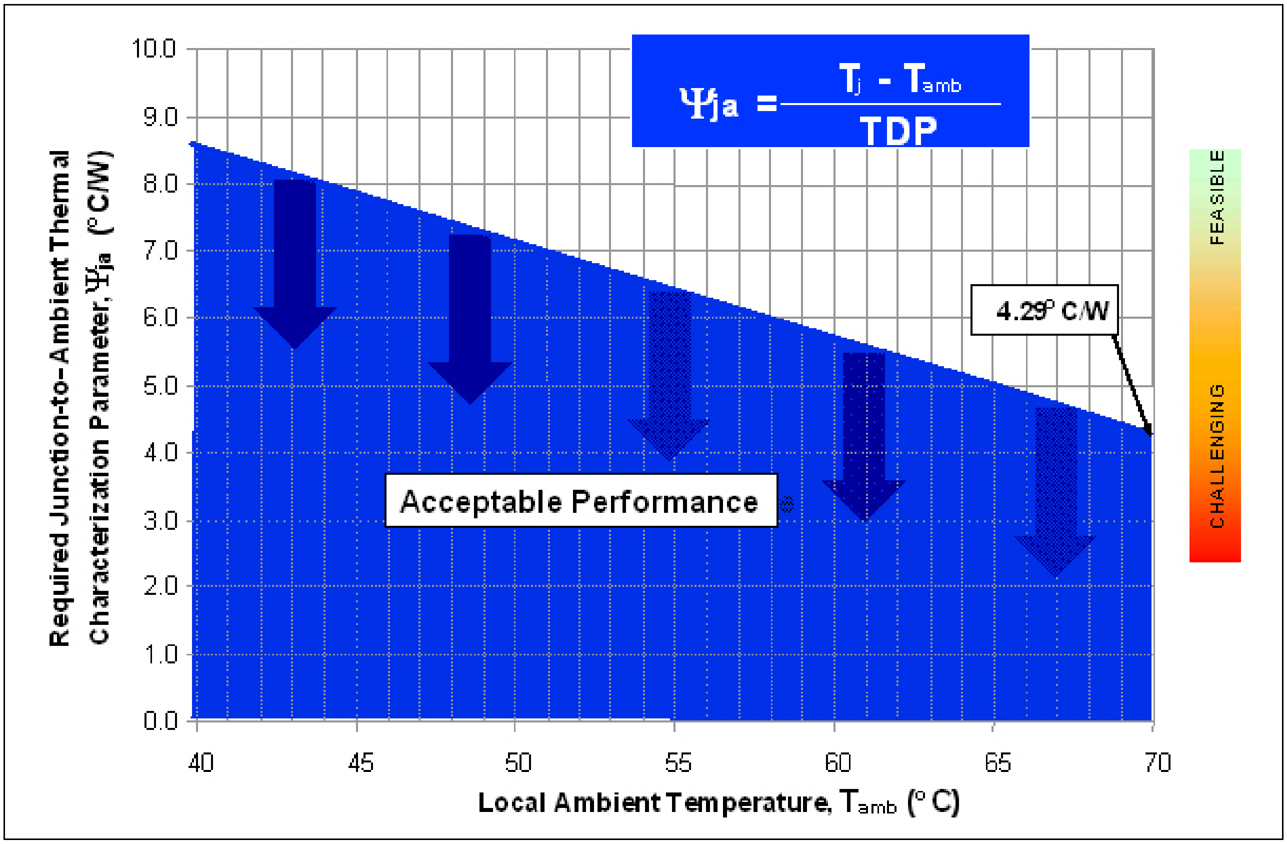
Figure 4. ULV Intel Celeron M Processor at 600 MHz Ψ_{ja} Requirements and Feasibility Scale for Passive Solutions

ULV Intel® Celeron® M Processor			Required Thermal Solution Performance at Various Ambient Temperatures					
			40°C	45°C	50°C	55°C	60°C	70°C
Frequency MHz	TDP Max (W)	Tj Max (°C)	Ψ ja (°C/W)	Ψ ja (°C/W)	Ψ ja (°C/W)	Ψ ja (°C/W)	Ψ ja (°C/W)	Ψ ja (°C/W)
600	7.0	100	8.57	7.86	7.14	6.43	5.71	4.29

Note: Specifications (TDP, Tj) provided for reference only. Refer to the latest datasheet for the most recent data.

$\Psi_{ja} = (T_{junction} - T_{amb}) / TDP$: junction-to-ambient thermal resistance for the thermal solution.

Figure 5. Required Thermal Performance as a Function of Ambient Temperature



3.2.3 Component Placement, System Orientation and Venting

The placement of heat generating components in a system has an influence in the ability to develop a natural convection thermal solution. The component placement should be optimized for a number of reasons, these include:

- Location of venting in the chassis: the vents in the chassis will allow external air that is at a lower temperature to enter the chassis and allow heated air to escape the system. For critical components with the highest amount of power generation (usually the CPU), it is necessary to place both the inlet and outlet vents as close to them as possible in the chassis. This will facilitate the movement of air caused by buoyancy effects hence minimizing the internal temperature rise, T_{rise}, caused by the recirculation of the hot air rising from the component but unable to exhaust out of the chassis.
- Orientation of the system: the orientation of the system influences where the components should be placed and the ability to develop a natural convection solution. If the system is in a vertical configuration, the processor should be placed at the bottom of the motherboard. This will allow for the air to rise and prevent any unnecessary pre-heating of the air surrounding the processor. When the system is in a horizontal configuration, the processor should be placed on the topside of the motherboard in order to avoid trapping the air underneath the board. The main goal of the component placement in regards to system orientation is to minimize the local ambient temperature and avoid placing the processor and other critical components in unfavorable boundary conditions.
- Maximize the effects of radiation from hot components while minimizing the effect of irradiation to the components: the proximity of the power generating components to each other will affect not only the local ambient temperature but will reduce the radiation heat dissipation from the components. High power dissipating parts should be placed as far from each other as motherboard size and electrical routing constraints allow.

The component placement, location of the vents, and the orientation of the motherboard directly influence the value of T_{amb} hence the ability to develop and optimize natural convection thermal solution. A well designed chassis that provides lower T_{amb} will in turn allow smaller and more cost effective thermal solutions to the critical components. It is highly recommended that thermal simulations and analysis be performed on a system level. A Computational Fluid Dynamics (CFD) program may be used to study multiple tradeoff scenarios, and system configurations can be modeled to optimize the thermal solution to meet component's thermal requirements. Proper system level thermal modeling allows the thermal solution designer to optimize thermal solutions and be confident in their performance prior to fabricating hardware. This results in better solutions, lower design time, and faster integration. More in-depth discussions and guidelines on the system level considerations are provided in the *Thermal Considerations for Passive Set Top Box Design Guide.*

3.2.4 ULV Intel® Celeron® M Processor at 600 MHz Thermal Specifications

Thermal data for the ULV Intel Celeron M processor at 600 MHz is presented in Table 3. The data is provided for informational purposes only. Please refer to the processor datasheet for the most up to date information. In the event of conflict, the processor's datasheet supersedes information provided in this document.

Table 3. Processor Thermal Specifications

Processor	Frequency (MHz)	Thermal Design Power (W)	Minimum Junction Temperature (°C)	Maximum Junction Temperature (°C)
ULV Intel Celeron M processor at 600 MHz	600	7.0	0	100

3.3 Processor Power

The processor power is specified as Thermal Design Power (TDP) for thermal solution design. TDP is defined as the worst-case power dissipated by the processor while executing publicly available software under normal operating conditions, at nominal voltages that meet the load line specifications. The TDP definition is synonymous with the Thermal Design Power (typical) specification referred to in previous Intel® data sheets. The Intel® TDP specification is a recommended design point and is not representative of the absolute maximum power the processor may dissipate under worst case conditions. For any excursions beyond TDP, the Thermal Monitor feature is available to maintain the processor thermal specifications. Refer to the processor datasheet for details regarding the Thermal Design Power specifications and Section 3.5 for the Intel® Thermal Monitor.

3.4 Thermal Diode

The ULV Intel Celeron M processor at 600 MHz incorporates two methods of monitoring die temperature, the Thermal Monitor and the thermal diode. The Intel Thermal Monitor must be used to determine when the maximum specified processor junction temperature has been reached. The second method, the thermal diode, can be read by an off-die analog/digital converter (a thermal sensor) located on the motherboard, or a stand-alone measurement kit. The thermal diode may be used to monitor the die temperature of the processor for thermal management or instrumentation purposes but cannot be used to indicate that the maximum $T_{junction}$ of the processor has been reached. The thermal diode can only be used for long term, steady state measurement of die temperature. It is not suitable for real time thermal management. For more information refer to the *ULV Intel Celeron M Processor Datasheet*.

Note: The reading of the external thermal sensor (on the motherboard) connected to the processor thermal diode signals will not necessarily reflect the temperature of the hottest location on the die. Sources of inaccuracies include:

- The external thermal sensor
- On-die temperature gradients between the location of the thermal diode and the hottest location on the die
- Time based variations in the die temperature measurement

Time based variations may occur when the sampling rate of the thermal diode by the thermal sensor is slower than the rate at which the T_j may change.

3.5 Thermal Monitor

The Intel Thermal Monitor helps control the processor temperature by activating the Thermal Control Circuit (TCC) when the processor silicon reaches its maximum operating temperature. The temperature at which the Intel Thermal Monitor activates the TCC is not user configurable and is not software visible. Bus traffic is snooped in the normal manner, and interrupt requests are latched and serviced during the time that the clocks are on while the TCC is active.

With a properly designed and characterized thermal solution, it is anticipated that the TCC would only be activated for very short periods of time when running the most power intensive applications. The processor performance impact due to these brief periods of TCC activation is expected to be so minor that it would not be detectable. An under-designed thermal solution that is not able to prevent excessive activation of the TCC in the anticipated ambient environment may cause a noticeable performance degradation, and may affect the long-term reliability of the processor. In addition, a thermal solution that is significantly under designed may not be capable of cooling the processor even when the TCC is active continuously.

The Intel Thermal Monitor controls the processor temperature by modulating (starting and stopping) the processor core clocks when the processor silicon reaches its maximum operating temperature. The Intel Thermal Monitor uses two modes to activate the TCC: Automatic mode and On-Demand mode. If both modes are activated, automatic mode takes precedence. The Intel Thermal Monitor Automatic Mode must be enabled via BIOS for the processor to be operating within specifications. This mode is selected by writing values to the Model Specific Registers (MSRs) of the processor. After the automatic mode is enabled, the TCC will activate only when the internal die temperature reaches the maximum allowed value for operation.

When Intel Thermal Monitor is enabled, and a high temperature situation exists, the clocks will be modulated by alternately turning the clocks off and on at a 50% duty cycle. Cycle times are processor speed dependent and will decrease linearly as processor core frequencies increase. After the temperature has returned to a non-critical level, modulation ceases and the TCC goes inactive. A small amount of hysteresis has been included to prevent rapid active/inactive transitions of the TCC when the processor temperature is near the trip point. The duty cycle is factory configured and cannot be modified. Also, the automatic mode does not require any additional hardware, software drivers or interrupt handling routines. Processor performance will be decreased by the same percentage as the duty cycle when the TCC is active, however, with a properly designed and characterized thermal solution the TCC most likely will never be activated, or will be activated only briefly during the most power intensive applications.

The TCC may also be activated using On-Demand mode. If bit 4 of the ACPI Intel Thermal Monitor Control register is written to a logic one, the TCC will be activated immediately, independent of the processor temperature. When using On-Demand mode to activate the TCC, the duty cycle of the clock modulation is programmable via bits 3:1 of the same ACPI Intel Thermal Monitor Control Register. In automatic mode, the duty cycle is fixed at 50% on, 50% off, in On-Demand mode, the duty cycle can be programmed from 12.5% on/ 87.5% off, to 87.5% on/12.5% off in 12.5% increments. On-Demand mode can be used at the same time automatic mode is enabled, however, if the system tries to enable the TCC via On-Demand mode at the same time automatic mode is enabled and a high temperature condition exists, automatic mode will take precedence.

An external signal, PROCHOT# (processor hot) is asserted when the processor detects that its temperature is above the thermal trip point. Bus snooping and interrupt latching are also active while the TCC is active.

Note: PROCHOT# will not be asserted when the processor is in the Stop-Grant, Sleep, and Deep Sleep low power states (internal clocks stopped), hence the thermal diode reading must be used as a safeguard to maintain the processor junction temperature within the 100 °C (maximum) specification. If the platform thermal solution is not able to maintain the processor junction temperature within the maximum specification, the system must initiate an orderly shutdown to prevent damage. If the processor enters one of the above low power states with PROCHOT# already asserted, PROCHOT# will remain asserted until the processor exits the low power state and the processor junction temperature drops below the thermal trip point.

If automatic mode is disabled the processor will be operating out of specification. Whether the automatic or On-Demand modes are enabled or not, in the event of a catastrophic cooling failure, the processor will automatically shut down when the silicon has reached a temperature of approximately 125 °C. At this point the FSB signal THERMTRIP# will go active. THERMTRIP# activation is independent of processor activity and does not generate any bus cycles. When THERMTRIP# is asserted, the processor core voltage must be shut down within the time specified in the processor datasheet.

3.6 Power Density and Non-uniform Heating

The ULV Intel Celeron M processor at 600 MHz die does not exhibit a uniform power distribution over its surface area. Non-uniform power distributions result in localized hot spots on the die surface, and they will adversely affect the overall thermal solution performance. The $T_{junction}$ is defined as the hottest hot spot temperature on the die. The processor density factor or the degree of power non-uniformity for the ULV Intel Celeron M processor at 600 MHz will be higher than on previous processors.

The Thermal Interface Material (TIM), which functions as the first layer of heat spreading above the die, will be most susceptible to non-uniform die power characteristics. Processor thermal solution designers must account for the increase in expected thermal impedance (or resistance) from the thermal interface material when it is attached to the processor die. Processor heat sink performance will not be affected to the same degree as the TIM. The performance of a heat sink is dependent on many factors, including heat sink size, base thickness, and materials used, but the impact of die non-uniform power on the heat sink performance can be considered insignificant for all practical purposes, as the magnitude is usually less than the uncertainty or variations typically associated with detecting or predicting the performance of the TIM. It is the responsibility of the OEM thermal solution designer to validate overall thermal solution performance in the intended system.

3.7 Processor Thermal Validations

The performance of a thermal solution is dependent on many parameters including the processor's maximum junction temperature, T_j, the operating ambient temperature, T_{amb}, the specific heat sink design, component materials, and the amount of airflow. In this document the designs are targeted for a natural convection environment, so there is no induced airflow. The guidelines and recommendations presented in this document are referenced to the parameter, T_{amb}, which relates the performance of a local heat sink solution to the local boundary conditions determined and provided by a given system. It is the responsibility of each product design team to ensure the target T_{amb} is achieved in a given chassis design and to verify that thermal solutions are suitable for their specific use.

4 Third Party Enabled Passive Solutions

A number of natural convection thermal solutions were analyzed, and a set of baseline heat sink designs optimized for the ULV Intel Celeron M processor at 600 MHz in natural convection applications were established for a typical set-top-box form factor. As stated in Section 3.2 it is very important to consider all system and component boundary conditions when designing a natural convection thermal solution.

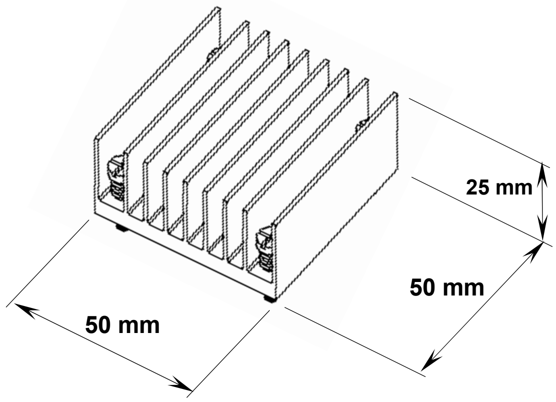
Based on the optimum heat sink parameters implemented in the baseline heat sink design, a number of passive heat sinks have been proposed by different suppliers for delivering the thermal performance required to cool the Intel Celeron M processor at 600 MHz over a range of T_{amb} variations as illustrated in Section 3.2.2, Figures 4 and 5. These heat sinks are a good fit for platforms requiring a passive thermal solution if the z-height allowed is similar to the heights typically allowed for ATX family form factor solutions. The following sections provide details on the different passive heat sink designs provided by a number of suppliers.

The performance predictions of the thermal solutions provided herein are for reference purposes only. These values were predicted based on a thermal solution stack-up commonly employed for cooling FCBGA CPU packages in a typical set-top-box environment. As such, they do not include any variations that may be introduced by employing different set of solution stack-up with respect to TIM and the retention mechanism, nor do they imply any statistical significance. It is up to the system integrator to perform validation in the final intended system, including the heat sink, attachment method, and thermal interface material.

4.1 Aavid Passive Heat Sink

The Aavid heat sink is a black anodized aluminum extrusion, delivered with a set of four spring loaded screws and pre-applied thermal interface material. Aavid recommends Thermagon T-pcm or T-mate2905 for TIM. These are phase change materials (PCMs) that are naturally tacky at room temperatures, requiring no adhesives or preheating. PCM means the material will change properties at elevated temperatures to increase thermal performance. An assembled part view is provided below. Dimensions are in mm.

Figure 6. Isometric View of Aavid Passive Heat Sink



The passive heat sink is made of 6063-T5 aluminum extrusion alloy and has been optimized for natural convection applications while meeting the form factor and retention mechanism constraints of a typical set-top-box system. A complete set of engineering drawings for the heat sink and the retention mechanism is provided in Figure 12 and Figure 13 in Appendix A.

Thermal performance, Ψ_{sa}, of this heat sink in natural convection cooling is provided in Table 4 for both anodized and non-anodized versions. Anodizing the heat sink surface enhances the radiation performance at an incrementally added cost. Typically it would increase the heat sink part cost by approximately 10%, but the performance gain of anodized heat sink is typically 10-20% over non-anodized parts. In natural convection applications, anodization or even thin surface painting often is a cost effective performance enhancement method. Using the predicted heat sink performance characteristics, the corresponding overall thermal performance of the component, Ψ_{ja}, is determined using a thermal network analysis. These parameters are tabulated below:

Table 4. Thermal Performance of Aavid Passive Heat Sink

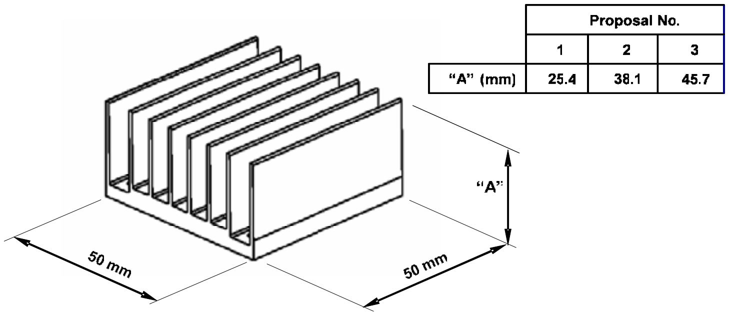
	Non-anodized	**Black Anodized**
Ψ_{sa} (°C/W)	6.3	5.2
Ψ_{ja} (°C/W)	6.8	5.7
T_{amb_max} (°C)	52	60

The corresponding local maximum ambient air temperature, T_{amb_max} , that can be supported by the heat sink solution is also included in the table. For example, the black anodized heat sink is capable of cooling a Celeron M processor at 600 MHz (TDP = 7W) with local ambient temperatures up to T_{amb} = 60°C without breaking the thermal specification of T_j =100°C.

4.2 Cooler Master Passive Heat Sinks

The Cooler Master heat sinks are aluminum extrusion, delivered with pre-applied thermal interface material (see Figure 14 in Appendix A). This material, Powerstrate* 51, manufactured by Power Devices, Inc., is a phase-change thermal interface material. This means the material will change properties at elevated temperatures to increase thermal performance. These phase change characteristics must be accounted for when testing the Cooler Master heat sinks. At low temperatures, the heat sink performance will be significantly degraded, but at elevated junction temperatures, the material will undergo a change phase and improve in performance. For more information, see the Power Devices website at: http://www.powerdevices.com. An isometric view of Cooler Master heat sinks is provided in Figure 7.

Figure 7. Isometric View of Cooler Master Passive Heat Sinks



	Proposal No.		
	1	2	3
"A" (mm)	25.4	38.1	45.7

These passive heat sinks are made of 6063-T5 aluminum extrusion alloy and have been optimized for natural convection applications while meeting the form factor and retention mechanism constraints of a typical set-top-box system. A complete set of engineering drawings for the heat sinks, retention mechanism, back plate, TIM and other parts of the total solution is provided in Figure 14 and Figure 15 in Appendix A.

Thermal performances, Ψ_{sa}, of this family of heat sinks in natural convection cooling with and without anodization are provided in Table 5. Anodizing the heat sink surface enhances the radiation performance at an incrementally added cost. Typically it would increase the heat sink part cost by approximately 10%, but as can be seen from the table the performance gain of anodized heat sinks are well over 20% over non-anodized parts. In natural convection applications, it is often the situation that anodization or even thin surface painting is a cost effective performance enhancement method. Using the predicted heat sink performance characteristics, the corresponding overall thermal performance of the component, Ψ_{ja}, is determined using a thermal network analysis. These parameters are tabulated below:

Table 5. Thermal Performance of Cooler Master Passive Heat Sinks

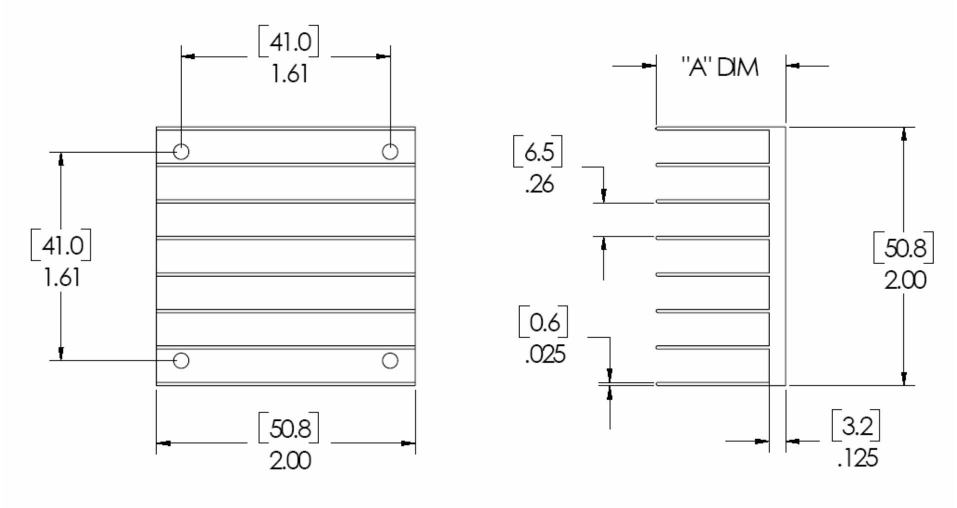
Surface Treatment	Clear Chromated			Black Anodized		
Proposal No.	**1**	**2**	**3**	**1**	**2**	**3**
Ψ_{sa} (°C/W)	6.7	5.2	4.6	5.3	4.2	3.8
Ψ_{ja} (°C/W)	6.9	5.6	5.0	5.7	4.7	4.3
T_{amb_max} (°C)	52	62	65	60	68	70

The corresponding local maximum ambient air temperature, T_{amb_max} , that can be supported by the heat sink solution is also included in the table. For example, the black anodized No. 3 heat sink is capable of cooling a Celeron M processor at 600 MHz (TDP = 7W) with local ambient temperatures up to T_{amb} = 70°C without breaking the CPU thermal specification of T_j =100°C.

4.3 ThermaFlo: Part No. 72010 Series

These passive heat sinks are made of 6063-T6 aluminum extrusion alloy and have been optimized for natural convection applications while meeting the form factor and retention mechanism constraints of a typical set-top-box system. A dimensional drawing is provided in Figure 8.

Figure 8. ThermaFlo Part No. 72010 Series Passive Heat Sinks



Part Number	"A" Dim
7201052	1.8"
7201053	1.5"
7201054	1.0"

Note: all dimensions are in inches

Thermal performances, Ψ_{sa}, of this family of heat sinks in natural convection cooling are provided by ThermaFlo based on the heat dissipation specifications of Intel Celeron M processor at 600 MHz. Using these heat sink performance characteristics, the corresponding overall thermal performance of the component, Ψ_{ja}, are determined using a thermal network analysis. These parameters are tabulated below:

Table 6. Thermal Performance of ThermaFlo Part No. 72010 Series Heat Sinks

Part No.	**7201052**	**7201053**	**7201054**
Ψ_{sa} (°C/W)	3.5	4.5	6.0
Ψ_{ja} (°C/W)	4.0	4.9	6.2
T_{amb_max} (°C)	72	66	56

The corresponding local maximum ambient air temperature, T_{amb_max} , that can be supported by the heat sink solution is also included in the table. For example, Part No. 7201052 is capable of cooling a Celeron M processor at 600 MHz (TDP = 7W) with local ambient temperatures up to T_{amb} = 72°C without breaking the CPU thermal specification of T_j =100°C.

The ThermaFlo part number designation for a complete set of heat sink solution kit, including TIM and attachment mechanism is “72010xx-Kit” where 72010xx is the part number of the corresponding heat sink.

4.4 Additional Heat Sink Designs

Multiple alternative heat sink designs have been enabled for the ULV Intel Celeron M processor at 600 MHz for systems that do not require a natural convection solution. These solutions are passive thermal solutions (with system airflow) and active fan sinks. For more information on heat sink details and performance curves refer to the *Intel Pentium M processor and Intel Celeron M Processor for Embedded Applications Thermal Design Guide* and *ULV Intel Celeron M processor at 600 MHz for Embedded Applications Thermal Design Guide.* A list of heat sink suppliers who also provide the total thermal solution set, including TIM and retention mechanisms, is provided in Section 5.1.

4.5 Recommended Thermal Interface Materials

It is important to understand and consider the effect of the interface between the processor and the heat sink base on the overall thermal solution. Specifically, the bond line thickness, interface material area, and interface material thermal conductivity must be selected to optimize the thermal solution.

It is important to minimize the thickness of the thermal interface material, commonly referred to as the bond line thickness. A large gap between the heat sink base and the processor die yields a greater thermal resistance. The thickness of the gap is determined by the flatness of both the heat sink base and the die, plus the thickness of the TIM, and the clamping force applied by the heat sink attachment method. To ensure proper and consistent thermal performance the TIM and application process must be properly designed.

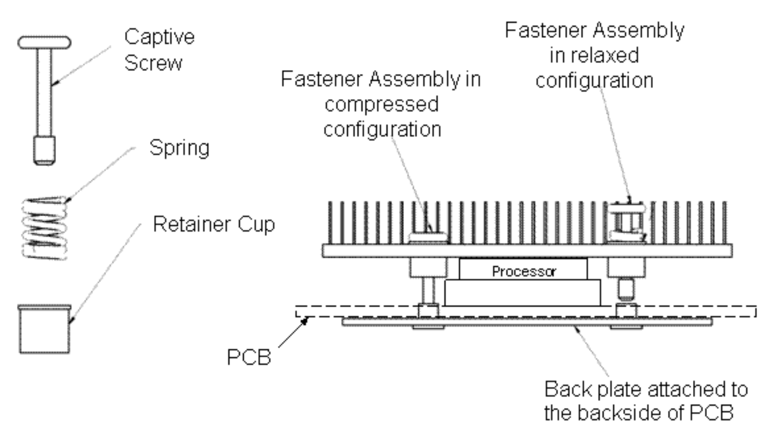
The heat sink solutions analyzed in this document are assumed to be using a high performance thermal interface materials, such as ShinEtsu* G751 thermal grease, or phase change material (PCM), such as Honeywell* PCM45f or Powerstate* PS51. Alternative materials may be used at the user's discretion. In the case of a bare-die FCBGA package, special attention may be necessary to comprehend the long-term reliability issues that may be caused by a pump-out situation where the TIM (i.e., grease type) is squeezed, over time, out of the interface. During the life of a product, it will go through a number of temperature cycles – the heating and cooling cycle as the component is turned on and off – which will cause the interface to expand and shrink as the mating surfaces expand and contract due to the thermal expansion and contraction. This causes an apparent pumping-out effect on the TIM and loss of the intimate thermal path at the interface. Although heat suppliers provide various TIMs as a part of total solutions, a list of vendors who specialize in TIM is provided in Section 5.2. The entire heat sink assembly, including the heat sink, attachment method, and thermal interface material, must be validated together in its final intended use.

4.6 Typical Attachment Methods

The thermal solution can be attached to the motherboard in a number of ways. The thermal solutions have been designed with mounting holes in the heat sink base. For a typical CPU heat sink solution, a fastening system consisting of screws and springs, secured with a fastener, should be used. The Cooler Master solution kit presented in this document (see Figure 13 in the appendix) employs this type of retention mechanism. The thermal solution is attached to the motherboard using a back plate that is fastened to the motherboard by four screws. This method of attachment uses spring-loaded fasteners to apply an even load on the processor die. The back plate, when assembled, will be flush against the backside of the motherboard. Refer to Figure 9 for an illustration of the assembly.

When the heat sink is light weight or the attachment requirement is less demanding, a plastic rivet is available that can be used to fasten the heat sinks. Examples of this type of fasteners are shown in Figure 17 in the appendix.

Figure 9. Sample Attachment Method



Depending on the system, the above example attachment types may or may not conform to secondary side CompactPCI* height requirements. Designs used in a CompactPCI* system must conform to maximum component height specifications on both the primary and secondary sides of the PCB. The entire heat sink assembly must be validated together for specific applications, including the heat sink, attachment method, and thermal interface material.

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5 Vendor Contact Information

5.1 Heat Sink Suppliers

Aavid Thermalloy LCC
80 Commercial Street
Concord, NH 03301 USA
Tel: 603-224-9988
e-mail: info@aavid.com
web: www.aavidthermalloy.com

CCI – Chaun Choung Technology Corp.
US: 2204 Forbes Drive, Suite 104
Austin, TX 78754
e-mail: eunice_chen@ccic.com.tw
APAC: F12, No. 123-1, Hsing-De Road
Sanchung City, Taipei, Taiwan
Tel: 886-2-29952666~8
e-mail: monica_chih@ccic.com.tw
Web: www.ccic.com.tw

Cooler Master Co., Ltd.
9F, No. 786, Chung Cheng Road,
Chung Ho city, Taipei, Taiwan, R.O.C.
Tel: +886-(0)2-32340050
Fax: +886-(0)2-32340051
e-mail: sales@coolermaster.com.tw
Web: www.coolermaster.com

ThermaFlo Inc.
3817 Old Conejo Road
Newbury Park, CA 91320 USA
Tel: 805-498-9991
e-mail: info@thermaflo.com
Web: www.thermaflo.com

Tyco Electronics Corporation
464 N. Halsted Court
Chandler, AZ 85225-4032
Tel: 480-857-0011
Web: www.tycoelectronics.com

5.2 Thermal Interface Material Suppliers

Berquist Company
18930 W. 78th Street
Chanhassen, MN 55317 USA
Tel: 800-347-4572
Web: www.berquistcompany.com

Chomerics
77 Dragon Court
Woburn, MA 01888 USA
Tel: 781-935-4850
E-mail: chomailbox@parker.com
Web: www.chomerics.com

Honeywell International Inc.
101 Columbia Road
Morristown, NJ 07962 USA
Tel: 973-455-2000
Web: www.honeywell.com

Power Devices Inc.
26941 Cabot Road, Bldg 124
Laguna Hills, CA 92653 USA
Tel: 949-582-6712
e-mail: power.devices@loctite.com
Web: www.powerdevices.com

Shin-Etsu Micro Si. Inc.
10028 S. 51st St.
Phoenix, AZ 85044
(480) 893-8898
Web: www.microsi.com

Thermagon, Inc.
4707 Detroit Avenue
Cleveland, OH 44102 USA
Tel: 216-939-2300
e-mail: info@thermagon.com
Web: www.thermagon.com

Appendix A: Mechanical Drawings

Table 6. Mechanical Drawing List (shown on the following pages)

Figure No.	Title
Figure 10	Natural Convection Small Form Factor Heat Sink Volumetric Constraint Zone (Primary Side).
Figure 11	Natural Convection Small Form Factor Heat Sink Volumetric Constraint Zone (Secondary Side).
Figure 12	Aavid Thermal Solution.
Figure 13	Aavid's Retention Mechanism
Figure 14	Cooler Master Thermal Solution.
Figure 15	Cooler Master's Retention Mechanism
Figure 16	ThermaFlo Thermal Solution
Figure 17	Fasteners: Pencom P/N PL 1664-65 and Fastex P/N 8034-00-9909.

Figure 10. Natural Convection Small Form Factor Heat Sink Volumetric Constraint Zone (Primary Side)

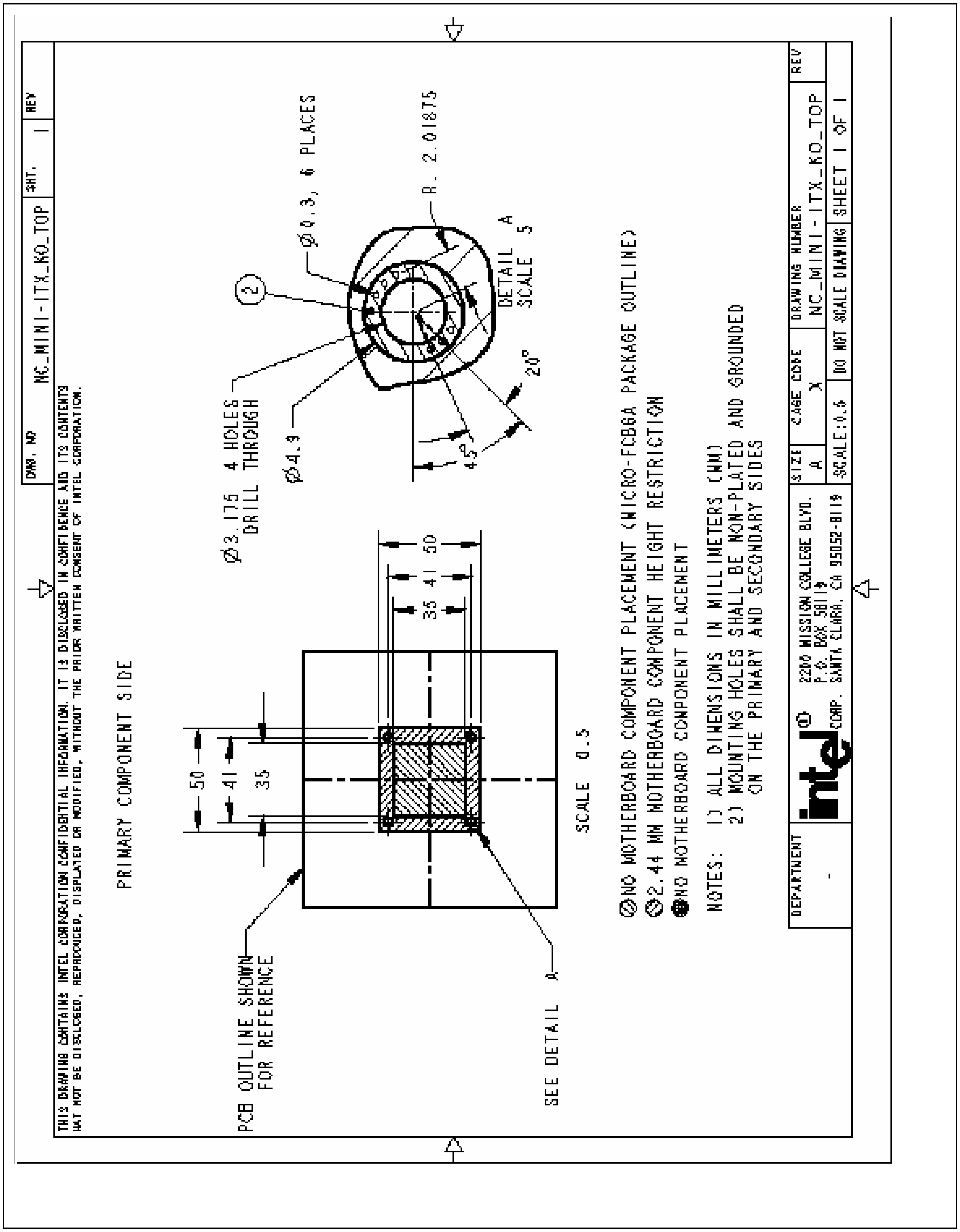


Figure 11. Natural Convection Small Form Factor Heat Sink Volumetric Constraint Zone (Secondary Side)

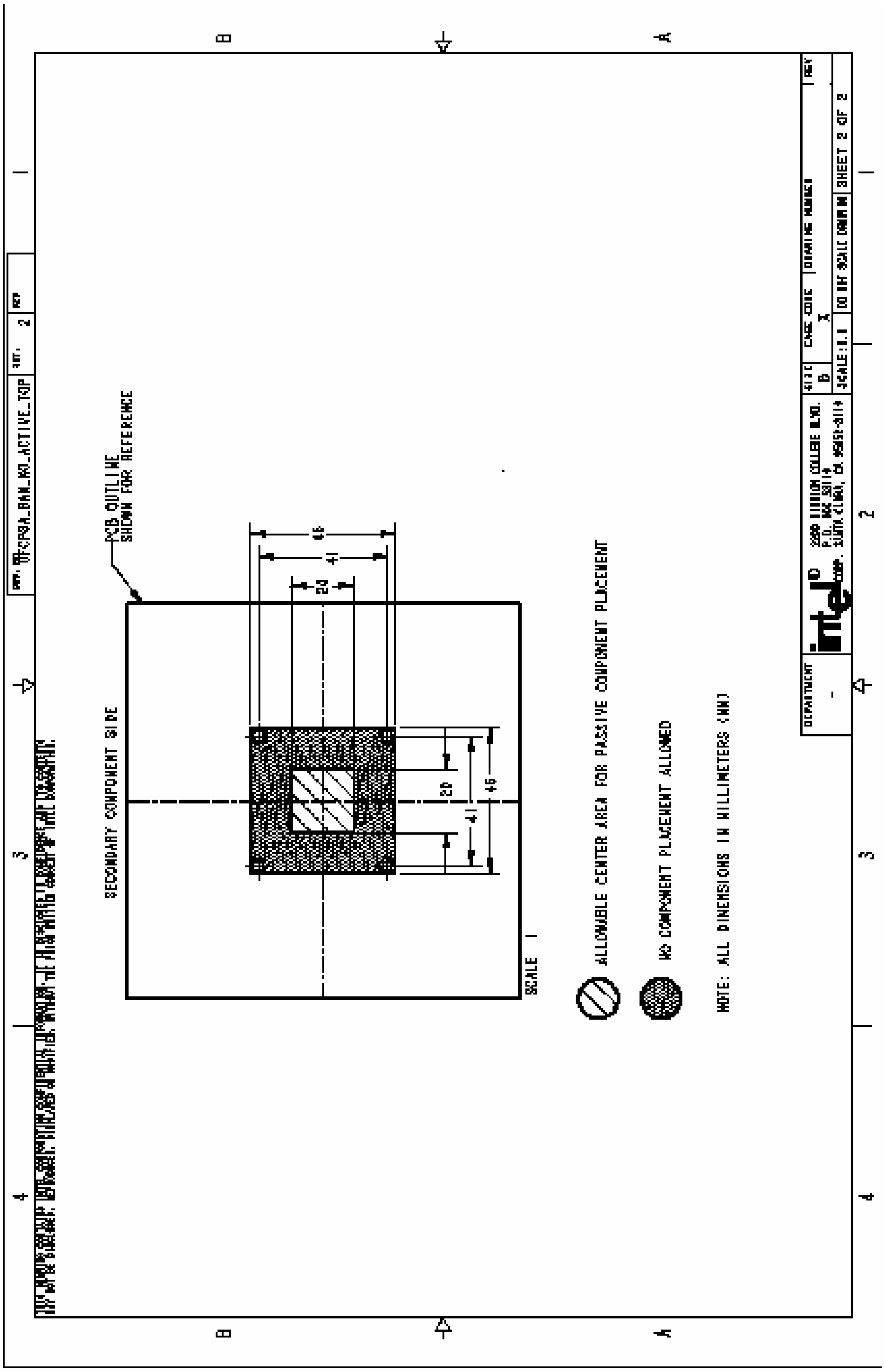


Figure 12. Aavid Thermal Solution

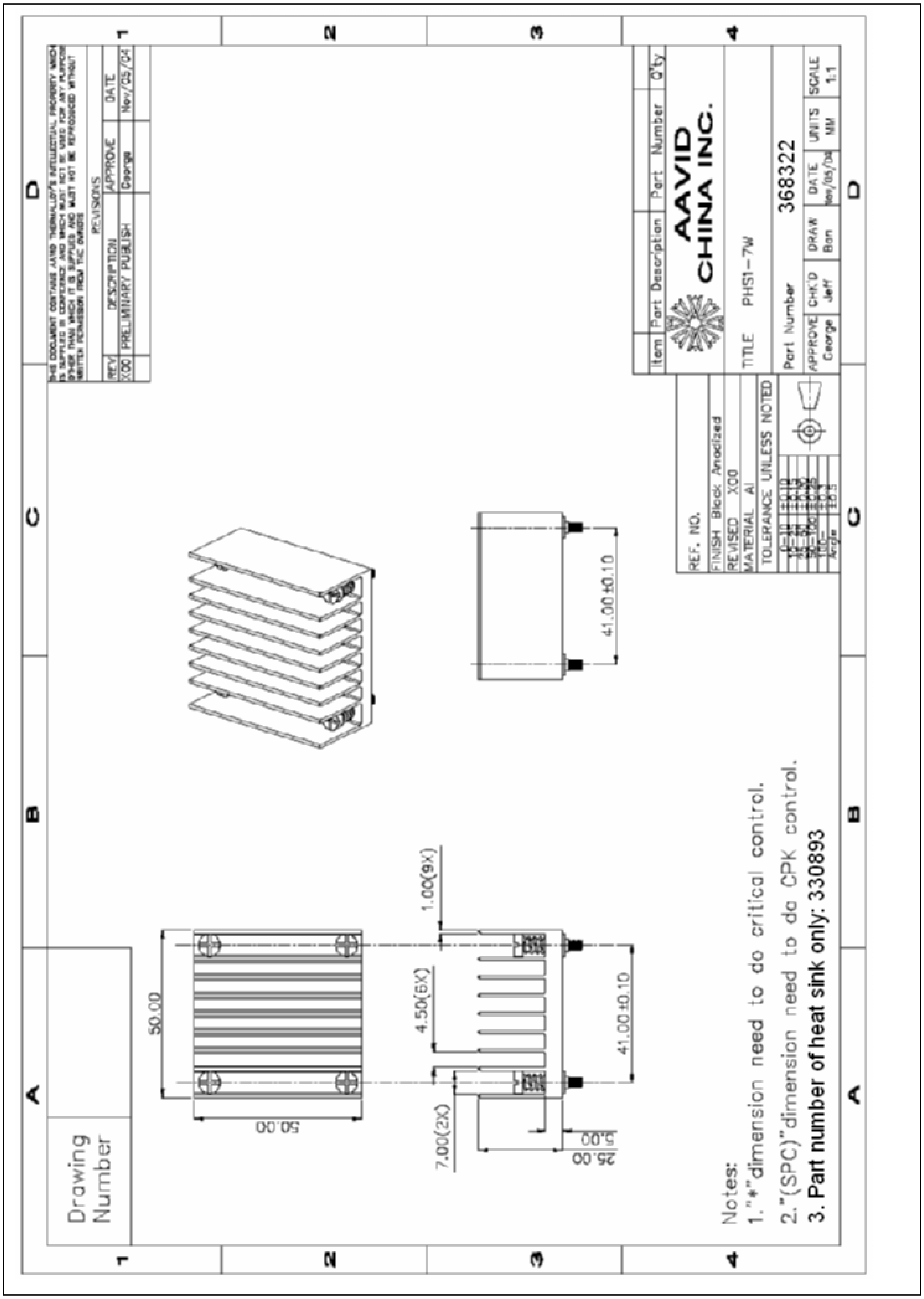
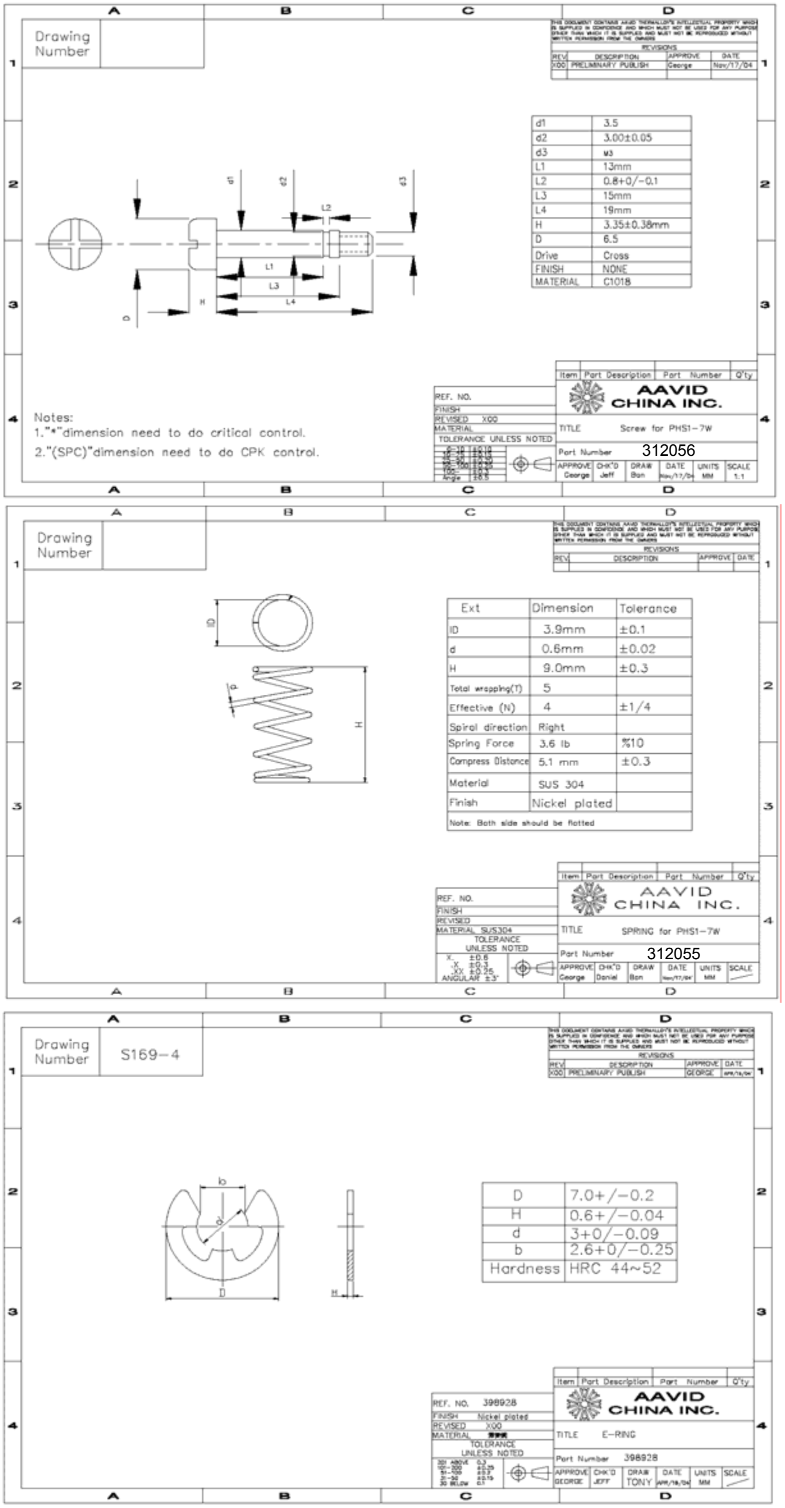


Figure 13. Aavid's Retention Mechanism

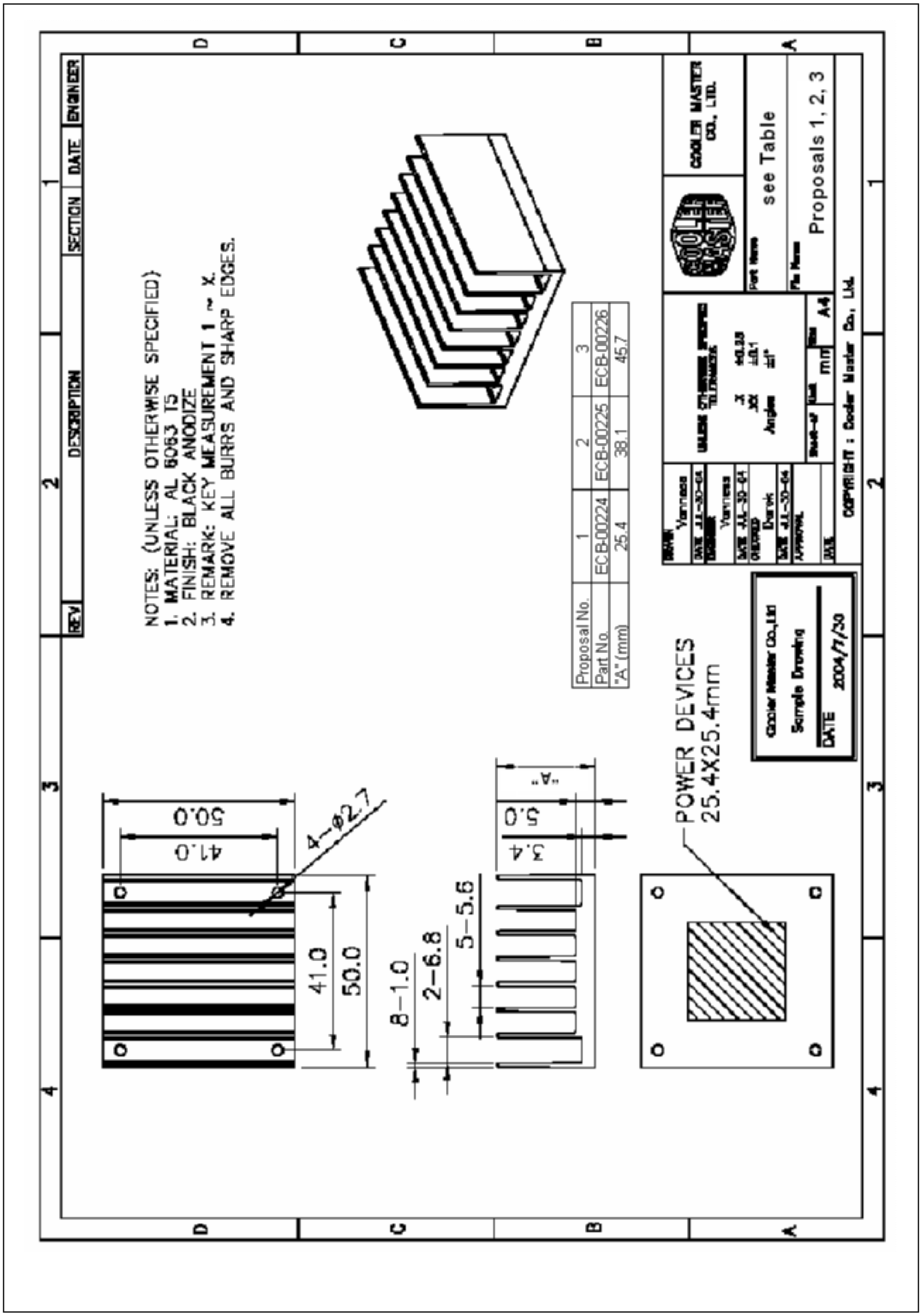


d1	3.5
d2	3.00±0.05
d3	M3
L1	13mm
L2	0.8+0/−0.1
L3	15mm
L4	19mm
H	3.35±0.38mm
D	6.5
Drive	Cross
FINISH	NONE
MATERIAL	C1018

Ext	Dimension	Tolerance
ID	3.9mm	±0.1
d	0.6mm	±0.02
H	9.0mm	±0.3
Total wrapping(T)	5	
Effective (N)	4	±1/4
Spiral direction	Right	
Spring Force	3.6 lb	%10
Compress Distance	5.1 mm	±0.3
Material	SUS 304	
Finish	Nickel plated	
Note: Both side should be flatted		

D	7.0+/−0.2
H	0.6+/−0.04
d	3+0/−0.09
b	2.6+0/−0.25
Hardness	HRC 44~52

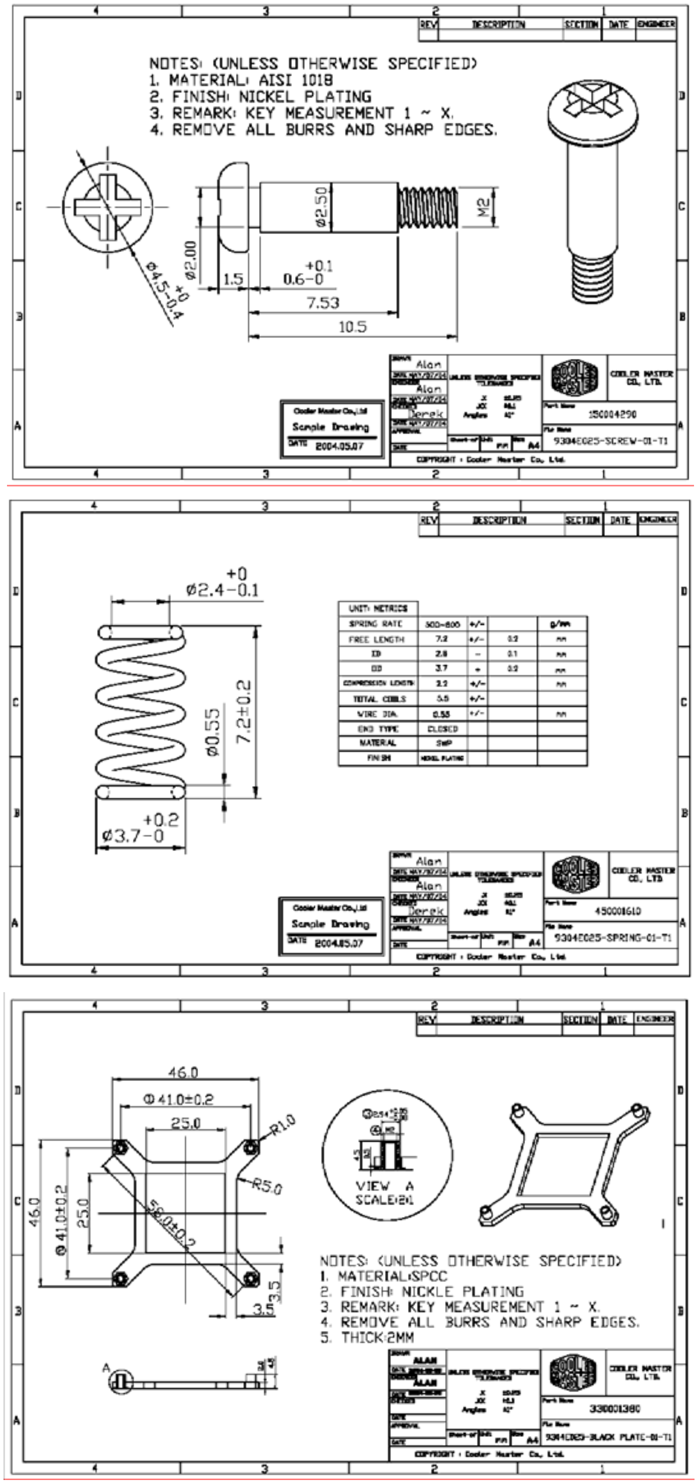
Figure 14. Cooler Master Thermal Solution



NOTES: (UNLESS OTHERWISE SPECIFIED)
1. MATERIAL: AL 6063 T5
2. FINISH: BLACK ANODIZE
3. REMARK: KEY MEASUREMENT 1 ~ X.
4. REMOVE ALL BURRS AND SHARP EDGES.

Proposal No.	1	2	3
Part No.	ECB-00224	ECB-00225	ECB-00226
"A" (mm)	25.4	38.1	45.7

Figure 15. Cooler Master's Retention Mechanism



NOTES: (UNLESS OTHERWISE SPECIFIED)
1. MATERIAL: AISI 1018
2. FINISH: NICKEL PLATING
3. REMARK: KEY MEASUREMENT 1 ~ X.
4. REMOVE ALL BURRS AND SHARP EDGES.

UNIT: METRICS				
SPRING RATE	500~600	+/-		g/mm
FREE LENGTH	7.2	+/-	0.2	mm
ID	2.8	-	0.1	mm
OD	3.7	+	0.2	mm
COMPRESSION LENGTH	2.2	+/-		mm
TOTAL COILS	5.5	+/-		
WIRE DIA.	0.55	+/-		mm
END TYPE	CLOSED			
MATERIAL	SWP			
FINISH	NICKEL PLATING			

NOTES: (UNLESS OTHERWISE SPECIFIED)
1. MATERIAL:SPCC
2. FINISH: NICKLE PLATING
3. REMARK: KEY MEASUREMENT 1 ~ X.
4. REMOVE ALL BURRS AND SHARP EDGES.
5. THICK:2MM

Figure 16. ThermaFlo Thermal Solution

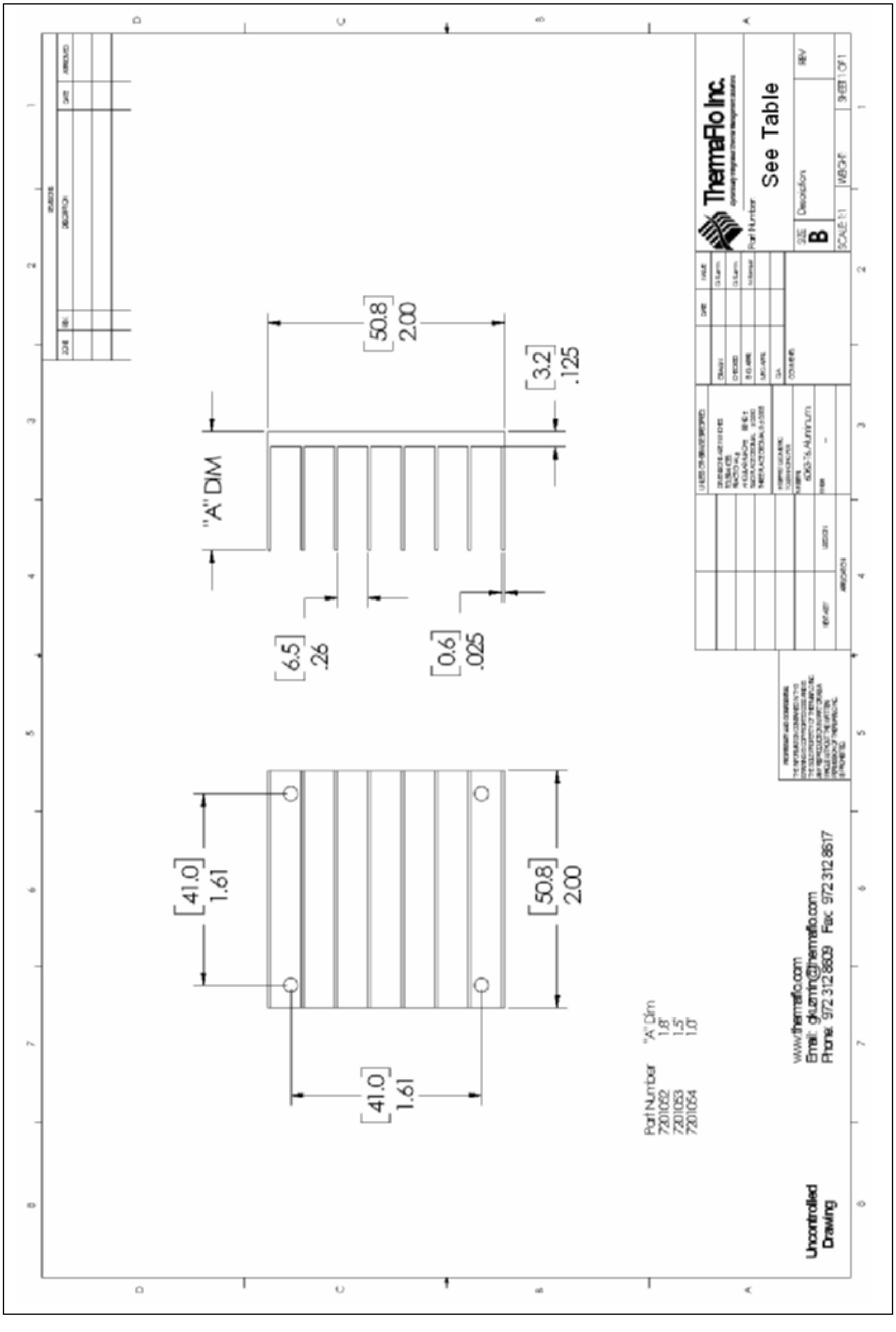
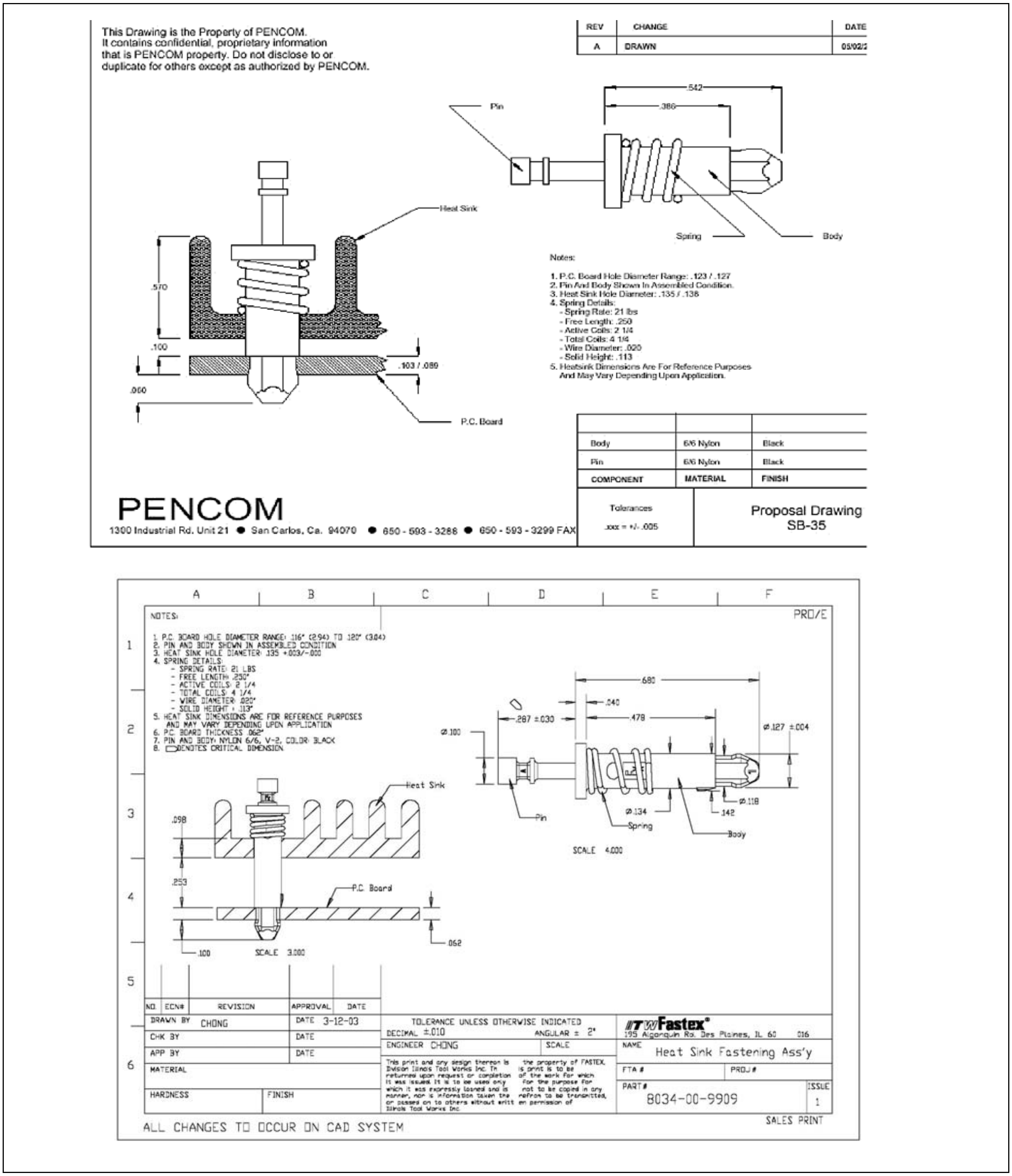


Figure 17. Fasteners: Pencom P/N PL 1664-65 and Fastex P/N 8034-00-9909



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