Freescale Semiconductor, Inc.

Application Note

AN2435/D
Rev. 0, 7/2003

Thermal Solutions for PowerPC™ Processors

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The products described in this document are PowerPC™ microprocessors. An often-asked question while designing a board using a PowerPC processor is whether or not a heat sink is needed with this processor. This document answers the question. Included is a method for determining the required thermal resistance of a heat sink.

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1 Heat Sink Requirements

First, let's look at the factors affecting whether we need a heat sink or not. Factors affecting the need for a heat sink are:

- Device power dissipation
- Board layout
- Ambient operating conditions
- Airflow (forced or still)

Device power dissipation affects the need for a heat sink. If the chip is cool enough it does not need a heat sink. Start thinking of heat sinks at 3 watts of power. It depends on the temperature difference between the maximum junction temperature and the ambient temperature.

Consider the other factors such as board layout and ambient operating conditions also. What does the board layout look like? Is it confined within a box? If it is surrounded by high power devices it can be heated up and needs a heat sink even when it would not need one if it was on a board by itself. The layout can increase the ambient temperature at the device. The fourth factor is air flow across the device. Is the board in still air, or is an air flow directed across the device? The typical home computer has not only a cooling fan attached directly to the processor but also a fan blowing forced air through the chassis.

1.1 Air Velocity Effects

The actual operating temperature within a given system varies, depending not only on the power dissipation of the actual part, but also on the system's cooling or heating specifics, such as the airflow, heat sinking capability, and other parameters.

Motorola manufactures devices and tests them to meet a commercial junction temperature range (0–105^{o} C). Use heat sinks and forced air to keep the junction temperature below our specified 105^{o} C.

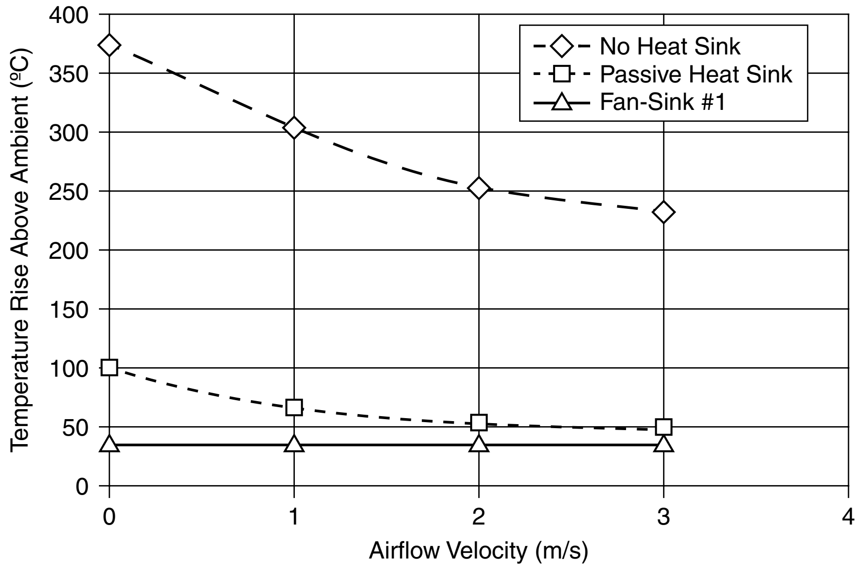

Figure 1. Air Velocity Effects and Heat Sink Effects on an MPC7450

Figure 1 indicates the effect that airflow and a typical heat sink have on the MPC7450. Notice that the passive heat sink reduces the temperature rise above ambient below 100^{o} C and the fan-sink reduces it below 50^{o} C. Remember that the graph without a heat sink is estimated and not actually proven by silicon. We would burn up the device at those temperatures.

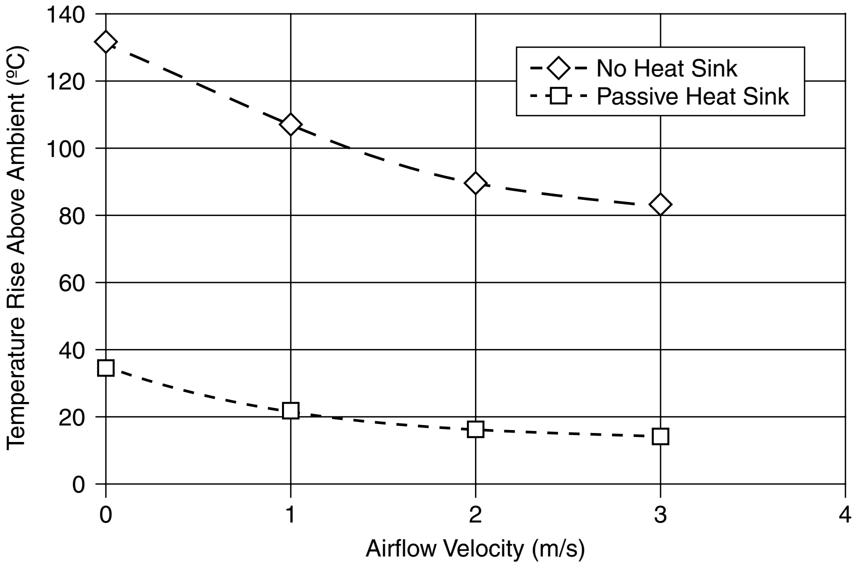

Figure 2. Air Velocity Effects and Heat Sink Effects on an MPC7410

Figure 2 shows the effect of airflow and a typical heat sink on the MPC7410. The heat sink reduces the temperature rise above ambient below 40^{o} C on this device.

1.2 Thermal Heat Path Flow

Figure 3 illustrates a CBGA device attached to a printed circuit board (PCB) with an attached heat sink. The heat sink is separated from the processor by a layer of interface material below which is the device, the ceramic substrate, balls, and the printed-circuit board.

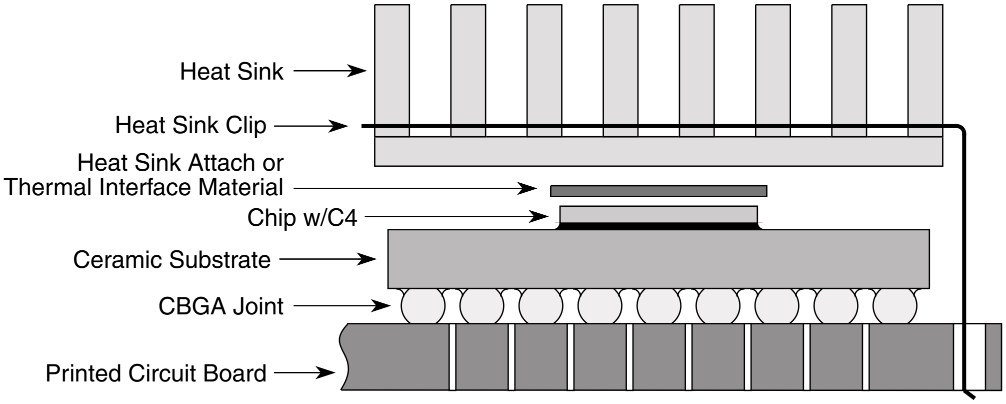

Figure 3. C4/Ceramic-Ball-Grid Array: Exploded Cross-sectional View with Optional Heat Sink (not to scale)

Figure 4 shows a simplified thermal network of a C4 ceramic ball grid array package mounted to a PCB.

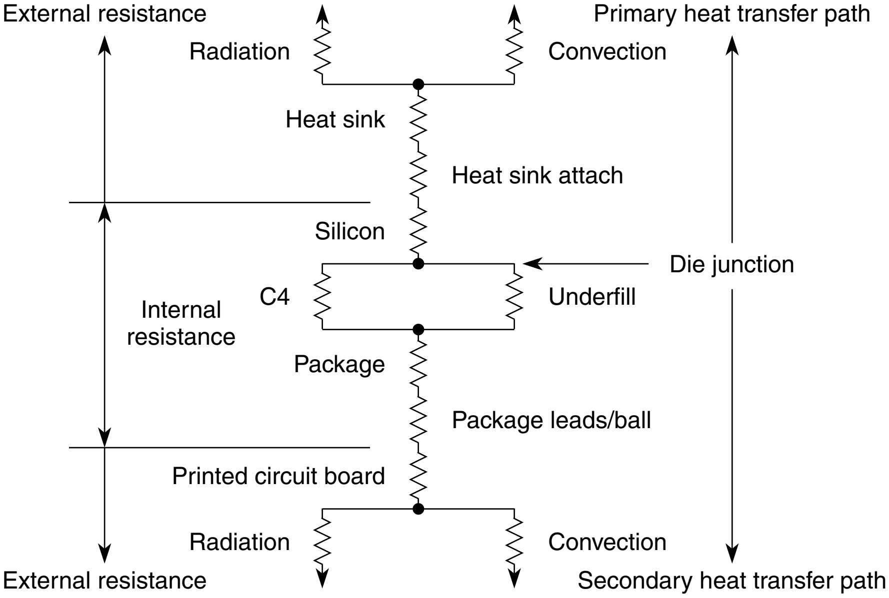

Figure 4. Simplified Thermal Network: a C4-Ceramic-Ball-Grid-Array Package Mounted to a Printed-circuit Board

In this CBGA package, the silicon chip is exposed; therefore, the package “case” is the top of the silicon (Figure 3). For cases with an attached heat sink, the primary heat transfer path is as follows: heat generated on the active side (ball) of the chip is conducted through the silicon, then through the heat sink attach material, and finally to the heat sink itself, where it is removed by natural or forced-air convection. This heat transfer model can be represented by the formula

$R_{\theta JA} = R_{\theta JC} + R_{\theta CS} + R_{\theta SA}$

where:

$R_{\theta JA}$ = the thermal resistance from the die junction to the ambient air

$R_{\theta JC}$ = the thermal resistance of the silicon from the die junction to the case

$R_{\theta CS}$ = the thermal resistance of the heat sink attach (interface material) from the case to the heat sink

$R_{\theta SA}$ = the thermal resistance of the heat sink from the heat sink to the ambient air

The silicon thermal resistance, $R_{\theta JC,}$ is quite small; therefore, for a first-order analysis, the temperature drop in the silicon may be neglected. Thus, the heat sink attach (or thermal interface) material and the heat sink conduction/convective thermal resistances are the dominant terms.

For lower-power microprocessors, the use of a heat sink may not be necessary. Heat conducted through the silicon may be convectively removed to the ambient air. In addition, a second parallel heat transfer path exists by conduction through the C4 bumps and the epoxy under-fill to the ceramic substrate for further convection cooling (see Figure 4). Then, from the ceramic substrate, heat is conducted via the leads/balls to the next-level of interconnect, whereupon the primary mode of heat transfer is by convection or radiation. Not using a heat sink may be adequate for low-power devices; however, that is a function of the board population and the system-level boundary conditions.

1.3 Board-Level Component Population Considerations

This section describes board-level interaction effects of similarly powered neighboring components. Board-level thermal flux rises with increasing component population, thereby limiting the ability of the PCB to act as a heat sink.

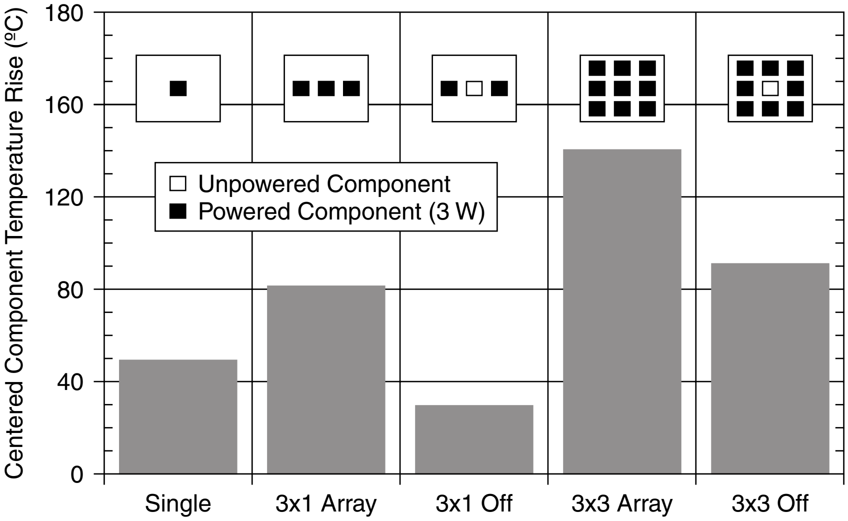

Figure 5. Interaction Effects of the MPC603 Microprocessor (3 watts) Temperature Rise above the Local Ambient with No Heat Sink

Using the MPC603 microprocessor with a 3W power dissipation and an air velocity of 2 m/s (with no heat sink), there is a considerable range in the die-junction component temperature rise, depending upon the board population, as shown in Figure 5. For the case of a single component mounted to a board, the die-junction temperature rise is approximately 50°C, while for a board populated with all nine components (all powered at 3 W), the center component temperature rise is approximately 135°C. Note that even if the center component is not powered, the die-junction component temperature rise is 90°C, due to heating from adjacent neighbors. This example demonstrates the need for microelectronics thermal engineers to conduct board-level and system-level thermal simulations to predict component operating temperatures accurately. In addition, because of the complex nature of heat transfer mechanisms, any models should be empirically validated.

Figure 6 shows the effect of the board's size on $R_{\theta JA}$, that is, the resistance from the junction to ambient air. As the effective size of the board increases and space increases to dissipate heat, the $R_{\theta JA}$ decreases. The resistance from the junction to ambient air differs also, depending upon whether the board is a single layer board (1s) or a multiple layer board (usually 2 signal, 2 planes or 2s2p). To distinguish between the two values, internally we report the value using the single layer board as $R_{\theta JA}$ and the value obtained on the 2s2p test board as $R_{\theta JMA}$.

The $R_{\theta JA}$ to use is determined by whether the application looks like a single package or an array. If it is like a single package or surrounded by only low power devices, use $R_{\theta JMA}$ and if it is like an array or surrounded by similar components or other high power devices, use $R_{\theta JA}$.

Warning:
An application on a real board may have less effective area to dissipate the heat than the 100x100 mm JEDEC board.

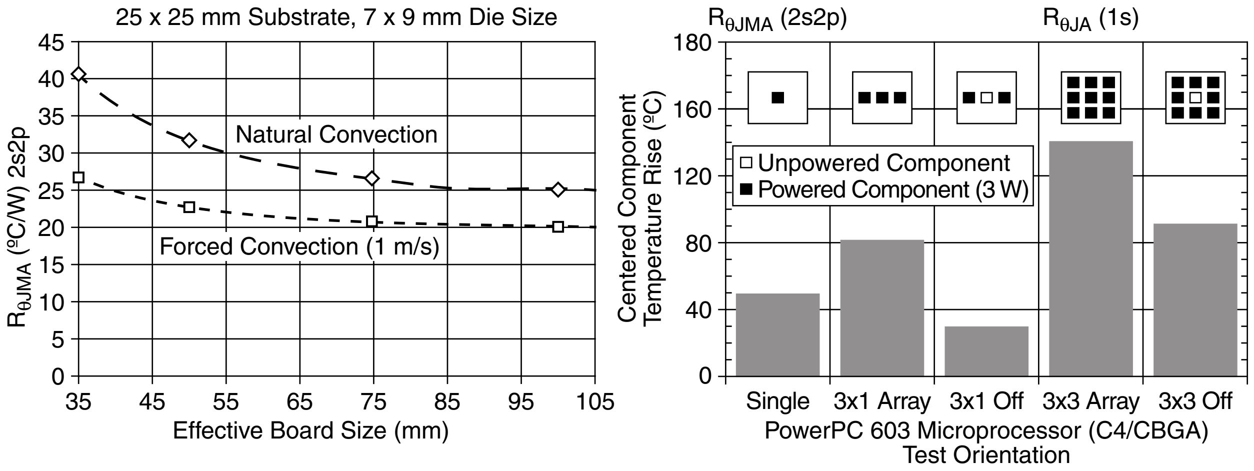

Figure 6. Effective Board Size and $R_{\theta JA}$ Selection

2 Determining Heat Sink Requirement

To determine the necessity of a heat sink, calculate the junction temperature using the formula $T_J = T_A + P * (R_{\theta JMA} \text{ or } R_{\theta JA})$. If the calculated junction temperature (T_J) is more than 105 ºC, a heat sink is required. Note that ambient temperature (T_A) is the temperature of the local ambient air near the component. Table 1 shows an example of the thermal resistance data found in Motorola hardware specifications. The table provides both the $R_{\theta JA}$ and $R_{\theta JMA}$ for the device in natural convection with an airflow of 200 ft/min, approximately 1 m/sec.

Table 1. Thermal Resistance Data for a 360LD 25x25 mm FC-CBGA (MPC755)

Rating	Board	Formula	Value	Unit	Notes
Junction-to-ambient natural convection	Single layer (1s)	$R_{\theta JA}$	26	°C/W	1, 2
Junction-to-ambient natural convection	Four layer (2s2p)	$R_{\theta JMA}$	19	°C/W	1, 3
Junction-to-ambient (@200 ft/min)	Single layer (1s)	$R_{\theta JA}$	20	°C/W	1, 3
Junction to ambient (@200 ft/min)	Four layer (2s2p)	$R_{\theta JMA}$	16	°C/W	1, 3
Junction to board	—	$R_{\theta JB}$	10	°C/W	4
Junction to case	—	$R_{\theta JC}$	< 0.1	°C/W	5

Notes:

1. Junction temperature is a function of on-device power dissipation, package thermal resistance, mounting site (board) temperature, ambient temperature, air flow, power dissipation of other components on the board, and board thermal resistance.
2. Per SEMI G38-87 and JEDEC JESD51-2 with the single layer board horizontal
3. Per JEDEC JESD51-6 with the board horizontal
4. Thermal resistance between the die and the printed circuit board per JEDEC JESD51-8. Board temperature is measured on the top surface of the board near the package.
5. Thermal resistance between the die and the case top surface as measured by the cold plate method (MIL SPEC-883 Method 1012.1) with the calculated case temperature. The actual value of $R_{\theta JC}$ for the part is less than 0.1º C/W.

2.1 Thermal Heat Sink Calculations (MPC755 example)

Using the information from Table 1, we can solve for the junction temperature. Assume an ambient temperature of 30°C and a thermal resistance of junction-to-ambient measurement of 26°C/W. This situation yields a junction temperature of 160°C, which is greater than the maximum specified junction temperature of 105°C. Even if the processor was on a board by itself, the junction temperature would still be 125°C, and a heat sink would be required.

$$T_J = T_A + P * (R_{\theta JMA} \text{ or } R_{\theta JA})$$

where:

$T_A = 30° C$

$R_{\theta JMA} = 19° C/W$

$R_{\theta JA} = 26° C/W$

$T_J = 30° C + (26° C/W) x 5.0 W$ $T_J = 30° C + (19° C/W) x 5.0 W$

$T_J = 160° C$ $T_J = 125° C$

This method is a little more definitive than touching the part with your finger to see if it is hot enough to cause a burn. After determining that a heat sink is necessary, decide which heat sink type to use.

2.2 Thermal Model when Heat Dissipates from Heat Sink

Take the formula in Section 2.1 and expand it. The formula for junction temperature (T_J) is now equal to the ambient temperature (T_A) , which we will replace with inlet cabinet ambient temperature(T_I) plus the air temperature rise within the cabinet (T_R) , plus power multiplied by the resistance from the junction to ambient ($R_{\theta JA}$). In this case, we will look at the junction to ambient temperature ($R_{\theta JA}$) as made up of the thermal resistance of the package ($R_{\theta JC}$), the thermal resistance of the interface ($R_{\theta CS}$), and the thermal resistance of the heat sink ($R_{\theta SA}$).

$$T_J = T_I + T_R + P * (R_{\theta JC} + R_{\theta CS} + R_{\theta SA})$$

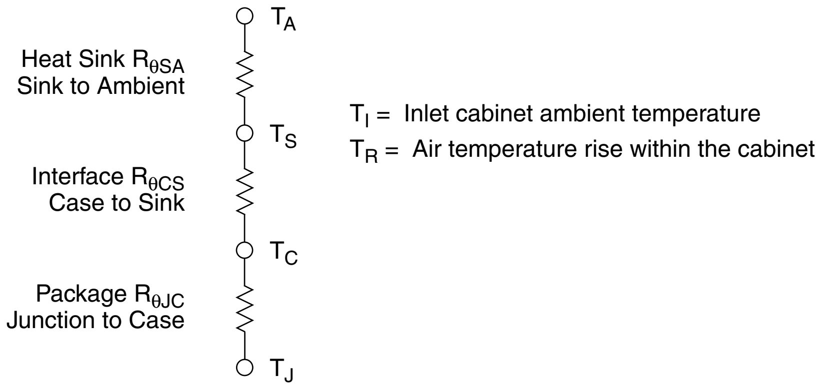

Figure 7. Thermal Model (Assume heat dissipated from heat sink)

2.3 Interface Material

For applications where the heat sink is attached by spring force or threaded, a thermal interface material at the die-to-heat sink interface can minimize thermal contact resistance. The graph in Figure 8 shows the thermal performance of three thin-sheet interface materials (silicone, graphite/oil, floroether oil), a bare joint, and a joint with thermal grease as a function of contact pressure. These thermal interface materials' performance improves with increasing contact pressure. Silicon die is fragile, and any heat sink attach scheme must accommodate structural compliance to avoid damage to the die. The use of thermal grease and a graphite/oil sheet significantly reduces interface resistance. Notice that the bare joint results in a thermal resistance approximately seven times greater than the thermal grease joint. These results may be used as a guide to show improvements that thermal interface materials offer over bare joints.

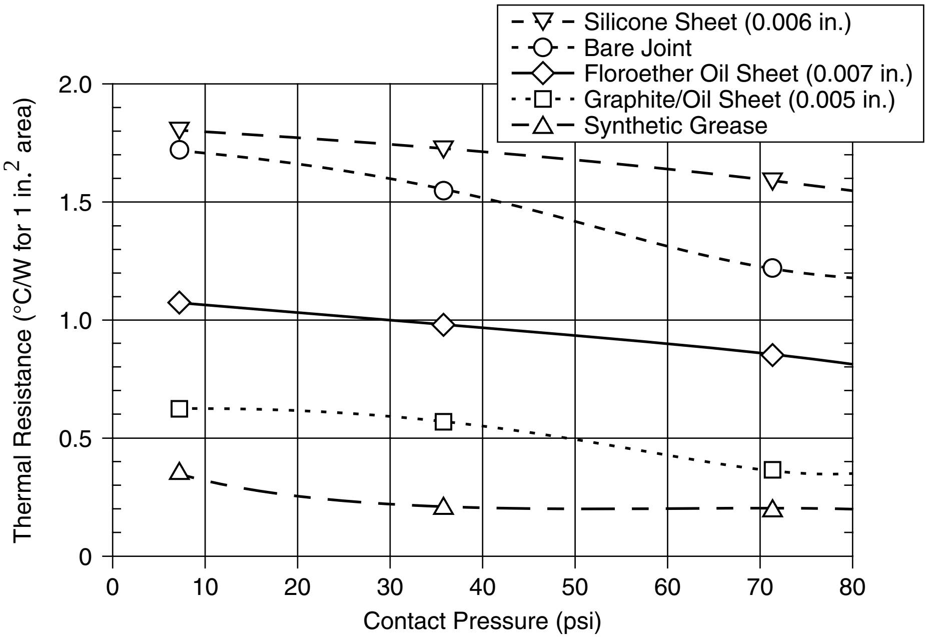

Figure 8. Interface Material Performance

2.4 Heat Sink Thermal Resistance

Figure 9 shows the thermal resistance of a typical heat sink, in this case a Thermalloy #2328B pin fin heat sink. Note the thermal resistance in degrees centigrade per watt against air flow. Resistance drops with increased airflow.

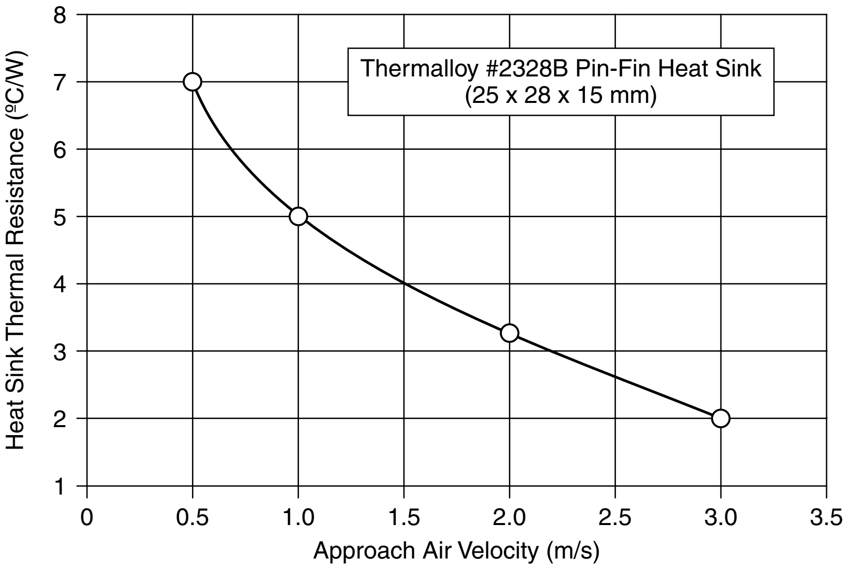

Figure 9. Heat Sink Resistance

2.5 Cooling Air Temperature

The temperature of the air cooling the component greatly depends on the ambient inlet air temperature and the air temperature rise within the computer cabinet before it reaches the component. A computer cabinet inlet air temperature may range from 30°C to 40°C. The air temperature rise within a cabinet may be between 5°C to 10°C. Thus, the allowable die-junction component temperature rise above ambient can range from 55°C to 70°C.

2.6 Thermal Model Calculations

To calculate the die-junction temperature using this formula, assume an inlet air temperature of 30°C and an air temperature rise within the computer cabinet before it reaches the component of 5°C. The thermal resistance of the thermal interface material ($R_{\theta CS}$) is typically about 1°C/W. Assuming a CBGA package, the $R_{\theta JC} < 0.1$°C/W. For a Thermalloy heat sink #2328B and assuming an air velocity of 0.5 m/s, we have an effective $R_{\theta SA}$ of 7°C/W (as shown in Figure 9), with a power consumption (Pd) of 5.0 W for the MPC755.

Thus,

$$T_J = T_I + T_R + (R_{\theta JC} + R_{\theta CS} + R_{\theta SA}) \times P$$

where: $T_I = 30°C$

$T_R = 05°C$

$R_{\theta JC} = <.1°C/W$

$R_{\theta CS} = 1°C/W$

$R_{\theta SA} = 7°C/W$

$$T_J = 30°\ C + 5°\ C + (0.1°\ C/W + 1.0°\ C/W + 7°\ C/W) \times 5.0\ W$$

$$T_J = 76°\ C$$

This calculation yields a die-junction temperature of approximately 76°C, which is well within the maximum operating temperature of the component.

If you did not have the heat sink information and wanted to know what kind of heat sink you needed, you could still solve the equation for the missing variable using a maximum junction temperature of 105°C. In this case you would find that you could use any heat sink that would give a thermal resistance of 12.9°C/W or less.

Other heat sinks sold by Aavid Thermalloy, Alpha Novatech, The Bergquist Company, IERC, Chip Coolers, and Wakefield Engineering offer different heat sink-to-ambient thermal resistances, which may or may not need airflow.

3 Heat Sink Mounting

Mechanical attachment to a PCB is preferable. If an adhesive attach is used, be sure to use pressure-sensitive adhesives such as Dow-Corning 1-4174 or similar silicone elastomer and small heat sinks only.

Motorola does not recommend a clip-to-package substrate approach for plastic laminate substrates without overmold.

4 Heat Sink Vendors

The following list includes heat sink vendors:

Aavid Thermalloy
80 Commercial St.
Concord, NH 03301
603-224-9988
www.aavidthermalloy.com

Alpha Novatech
473 Sapena Ct. #15
Santa Clara, CA 95054
408-749-7601
www.alphanovatech.com

International Electronic Research Corporation (IERC)
413 North Moss St.
Burbank, CA 91502
818-842-7277
www.ctscorp.com

Tyco Electronics
Chip Coolers™
P.O. Box 3668
Harrisburg, PA 17105-3668
800-522-6752
www.chipcoolers.com

Wakefield Engineering
33 Bridge St
Pelham, NH 03076
603-635-5201
www.wakefield.com

5 Interface Material Vendors

The following list includes interface material vendors:

The Bergquist Company
8930 West 78th St
Chanhassen, MN 55317
800-347-4572
www.bergquistcompany.com

Chomerics Inc.
77 Dragon Cour
Woburn, MA 01888-4014
781-935-4850
www.chomerics.com

Dow-Corning Corporation
Dow-Corning Electronic Materials
2200 W. Salzburg Rd.
Midland, MI 48686-0997
800-248-2481
www.dow.com

Shin-Etsu MicroSi, Inc.
10028 S. 51st St
Phoenix, AZ 85044
888-642-7674
www.microsi.com

Thermagon Inc.
4707 Detroit Ave.
Cleveland, OH 44102
888-246-9050
www.thermagon.com

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