PowerPC970MP Thermal Considerations

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Abstract

The 64-bit PowerPC970MP™ (970MP) is an enhanced dual processor version of the PPC970FX microprocessor. The 970MP contains two complete 64-bit microprocessor cores, dual 1-MB L2 caches, and Processor Interface (PI) bus, and bus arbitration logic. This paper will focus on the cooling requirements and proposed solution in two different applications. The first application is a 50 watt blade. The second example will focus on a low power, 28 watt paper application. Developing an appropriate thermal management solution is necessary for the proper operation and longevity of the end product.

The PowerPC 970MP

The PowerPC970MP dual 64-bit core microprocessor is a new standard in high performance computing. The processor chip contains two 64-bit microprocessor cores with dual, one-megabyte L2 caches, plus Processor Interface bus and arbitration logic. The higher clock rate versions of the processor can dissipate more than 70 watts. This power level is not uncommon with today's higher performance microprocessors, but can be a significant amount of power to manage. The task can only be completed successfully with careful design and engineering practices.

In all cases the 970MP must have some form of cooling solution. The processor dissipates enough power at the lowest operating frequency that direct air cooling is not sufficient. The type of cooling solution, metal or heat pipe based depends upon the application and its environmental constraints; low temperature, restricted air flow, confined space, high altitude operation, etc. If there are any concerns about thermal design competency, the designers should work with heatsink vendors to arrive at the best solution for the application.

Before the main design task can begin, background work must be done. These tasks include, reviewing the basics of thermal management, the basic physical and thermal characteristics of the PPC970MP chip, and operating environment. Basic thermal management information is available from many different heatsink vendors and volumes have been written on the subject. The thermal characteristics of the 970MP are contained in the Datasheet. This application note will revisit the very basics of thermal design and present two paper designs for review. The paper designs are targeted towards a 'typical' Server Blade application.

Basics of Heat Flow in the Semiconductor

When thinking about thermal management of the microprocessor one must know where the heat is generated and from where heat can be extracted. With the PPC970MP, heat is generated in the 153mm² die that sits on top of the square 25mm ceramic package. Heat energy is extracted from the exposed, backside of the die. Figure 1 shows the general outline of the chip and key package dimensions. Always review the latest version of the PPC970MP datasheet for the most up to date information. Additionally, other issues must be considered: airflow, operating environmental conditions, system thermal modeling, and heatsink attachment method.

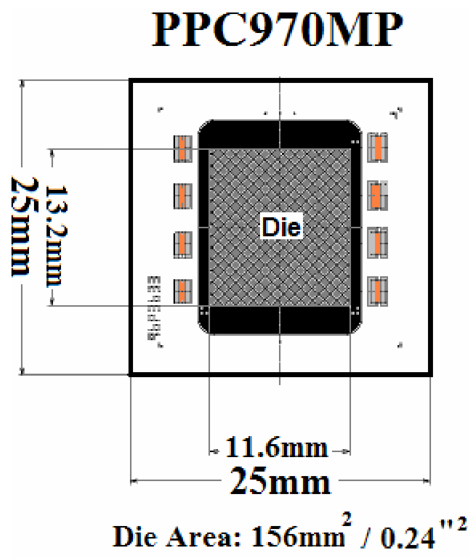

Figure 1. Basic PPC970MP package out line

PowerPC970MP Package Properties

After reviewing the thermal resistance specifications of the microprocessor, see Table 1, the majority of the thermal energy must be removed from the exposed backside of the microprocessor die. Basically, the values imply that comparatively little heat, < 2%, will flow out of the chip through the ceramic package and out to the PCB via the solder ball.

Thermal Characteristic	Value
CBGA thermal conductance to back of die: **ΘJC**	0.1 °C/W
CBGA thermal conductance to PCB: **ΘJB**	5.4 °C/W

Table1. Thermal Characteristics of the PPC970MP microprocessor die and package

Realistically, all of the heat energy must be removed from the exposed die on top of the package. Heat energy is then moved into some type of heatsink where it is ejected into a cooling medium, usually forced air. Again, the PCB cannot be relied on to remove any useful amount of heat from the package.

In higher performance/space constrained applications it is recommended that a Computational Fluid Dynamics (CFD) package be used to model the final application's air flow and heat removal characteristics. The microprocessor can be modeled in detail, using a full thermal model of the chip, or in a simplified model. The decision rests upon the requirements of the final application. Note: The 970MP package details are available upon request.

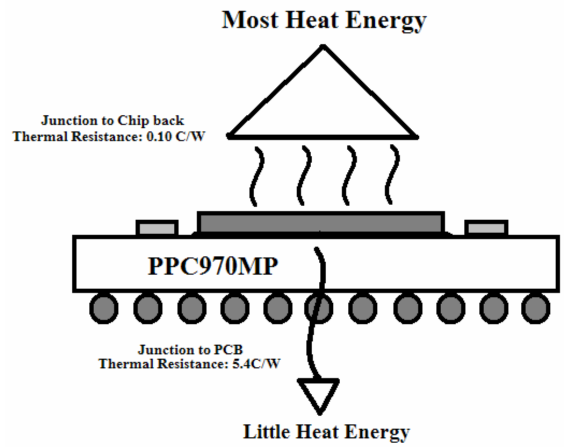

Figure 2. Basic Heat flow through PPC970MP

Thermal Interface Materials

A critical item that is sometimes over looked is the choice of Thermal Interface Material (TIM). If the mounting surfaces of the heatsink and die were perfectly flat and planer, thermal interface material would not be needed and the maximum theoretical amount of heat energy could be transferred across the interface. In the real world heatsinks are machined or cast pieces of metal that usually have irregular surfaces with pits and scratches. The main function of thermal interface material is to fill in the surface deformities and irregularities on the mating surfaces of the heatsink and processor die. Thermal interface materials improve heat transfer by filling in the surface irregularities, displacing poorer conducting air in those voids, maximizing thermal conduction between the die and heatsink.

There are a wide variety of TIMs. Commonly available TIMs fall into three general categories, thermal greases, phase change materials, and thermal glues. Each has its benefits, greases generally offer the best thermal transfer values, come in a wide range of thermal conductivity values, and are easily rework able though a little messy. Phase change materials are easy to apply, require one or more thermal excursion to the transition point of the material to reach its best performance, and must be heated above the transition point to be reworked. Thermal adhesives generally are not as conductive as phase change and greases. The glues can impose other dynamic force limits on the design. There are a variety of thermal interface materials that fall outside of these simple categories, for example, isothermal graphite or pads. Of course, this brief description of thermal interface materials is greatly simplified for this application note. Better descriptions of the thermal interface materials are available on vendor’s websites and in appropriate texts. A small starter list of different heatsink, TIM, and pressure film manufacturers is presented later in the document.

The higher performing microprocessors dissipate higher amounts of energy. Better thermal interface materials must be considered for the higher performing parts. These improved thermal interface materials reduce the temperature drop across the heatsink to die interface.

Basic Mechanical Considerations of the PPC970MP

The PPC970MP package is composed of an exposed bare silicon flip-chip die mounted on a 575-ball ceramic package. The microprocessor die is mounted to the ceramic package via ‘C4’ balls, Controlled Collapse Chip Connection, which are very small solder balls. The tiny space between the ceramic package and die is ‘underfilled’ with an epoxy compound. This protects the die to package interface and increases the heatsink mounting force by improving support of die. There are two general mounting constraints on this type of package and they can be confusing. First there is the force applied to the back of the die. This is specified as 30 pounds force against the die to package. The second value is the die to Printed Circuit Board (PCB) force and it is 20 pounds. Therefore, for a majority of applications the heatsink to PCB mounting force is the limit. If the processor to PCB gap is underfilled, mounting pressure can be increased to 30 pounds. The main benefit form increasing the heatsink to die pressure is to improve heat transfer across the thermal interface material, effectively reducing the temperature of the die. Next issue to attend is the dynamic forces imposed by the heatsink on the processor. If mounting or dynamic forces are exceeded, the die can be chipped, crushed, or otherwise damaged.

Note: Review the IBM white paper," Improving Chip to PCB Thermo-Mechanical Integrity" for a discussion of the function and possible benefits of package underfill.

Supporting a heatsink of sufficient size to dissipate the expected thermal load and compress the thermal interface material and minimize the thermal drop at these force levels can be a taxing problem to solve. The heatsink mounting method, springs, clips, screws, or others is heavily dependent upon the type of heatsink chosen, the enclosure, mounting constraints, and other mechanical concerns. The final mounting solution must both maintain pressure against the die and securely attach the heatsink to the PCB across the expected shipping and operating conditions. Pressure indicating film can be used to gage the pressure distribution and uniformity across the die to heatsink interface. Heatsink vendors will be able to help with the mounting strategies ensuring that the microprocessor die is not damaged by the heatsink.

Basic Power Discussion

Realistically, most applications that use the PPC970MP will use some form of metal heatsink, aluminum and/or copper. These are low cost, proven technology with no moving parts, and only require moving air to cool. In more high performance/constrained applications more complicated/exotic solutions may be needed ranging from fan sinks, heat pipe based heatsinks or liquid cooling.

Note: One point to remember is that all of these devices have fins on them to move the heat energy out of the heatsink and into the cooling airflow. More fins do not necessarily mean better cooling. More fins can impede airflow through them reducing the effective cooling capacity of the heatsink.

The first application to be investigated is a 1U server blade. The power dissipation of the PPC970MP, 50 watts in this example, makes standard all metal heatsinks a plausible solution if space allows and airflow is appropriate. In more space constrained applications water cooling or heat pipe based heatsinks should be investigated. These technologies allow heat energy to be removed from the processor and moved to another location to be ejected in the cooling medium. In this specific case of a 1U Server Blade with its limited space around and above the processor, aluminum and copper heatsinks may not work. The key is having enough room for airflow and a heatsink large enough to move heat from the processor to the cooling air.

Heat Pipe Cooling

Heat pipes are partially evaluated closed tubes/chamber partially filled with a working fluid and a wick material. See Figure 3 for a vapor chamber version of a heat pipe. Heat flows into one end/side of the pipe, where the microprocessor die attaches to it, and the working fluid evaporates. The vapor flows to the cold end/side of the pipe and condenses with nearly zero transfer resistance. The condensed liquid then is pulled back to the hot side of the heat pipe by gravity and the capillary action of the wick. Heat pipe-based heatsinks move heat away from the processor's die quickly and redistributes the heat energy to the cold fin side of the pipe where it is ejected into the ambient air. Vendor web sites contain more detailed description of how these devices work.

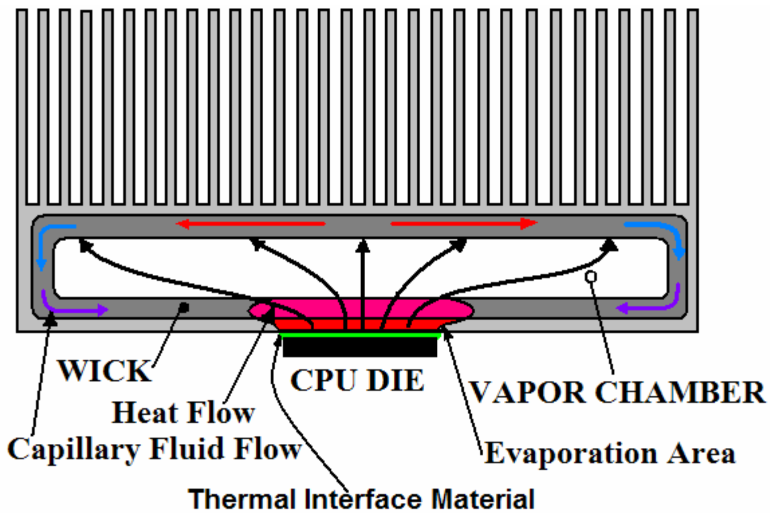

Figure 3. Basic Heatpipe Layout, Vapor Chamber Example

There are limits to what heat pipes can do. Heat pipes can be sized to carry from watts to kilowatts of power. For a given temperature gradient, heat pipes can transfer significantly more heat than even the best solid metal conductor, but when driven beyond the pipe's rated capacity the effective thermal conductivity of the heat pipe will be drastically be reduced. Standard heat pipes are limited to moving 60 to 80 watts cm^2 from the heat source. The heat transport capability of the heat pipe is governed by several limiting factors: viscous, sonic, capillary pumping, entrainment/flooding, and boiling. Usually the main limiting factor is the capillary pumping function. Also affecting this pumping efficiency is the orientation of the heatsink to gravity. Gravity is used to assist the capillary action that pulls the cooled fluid back to the heating area. If the heatsink is properly oriented, the main cooling limit is approached when the heat input to the heat pipe exceeds the pumping force of the wick structure returning the cooling fluid back to the evaporator. Basically, if the power density of the microprocessor exceeds the maximum heat density that the heat pipe will support, the system will stop working. The fluid in the pipe will boil away faster than it can be replenished. This situation could allow the microprocessor to over heat and fail.

Liquid Cooling

An exotic thermal management solution is liquid cooling. Heat energy is removed from the microprocessor using a cold plate, transferred to a liquid, usually water, and ejected to the environment using a radiator. The cold plate's function is to efficiently remove heat from the source and transfer it to the cooling fluid. There are several different types of cold plates, from sintered metal cold plates (Thermacore™) to high aspect ratio parallel fin cold plates (Cooligy™), see figure 4. A benefit of liquid technology is that the cold plate is much smaller than any heatsink, has much lower mass, and is easier to mount. In addition, the radiator can be located away from the heat generating sources and mounted in many orientations. The major drawbacks are: the addition work involved in designing and mounting the complete system, pump longevity, plumbing, and simply the change in mindset to using a liquid to cool the part.

Note: Please review the websites presented at the end of this note for detailed discussions of heat pipe-based and water-cooled heatsinks.

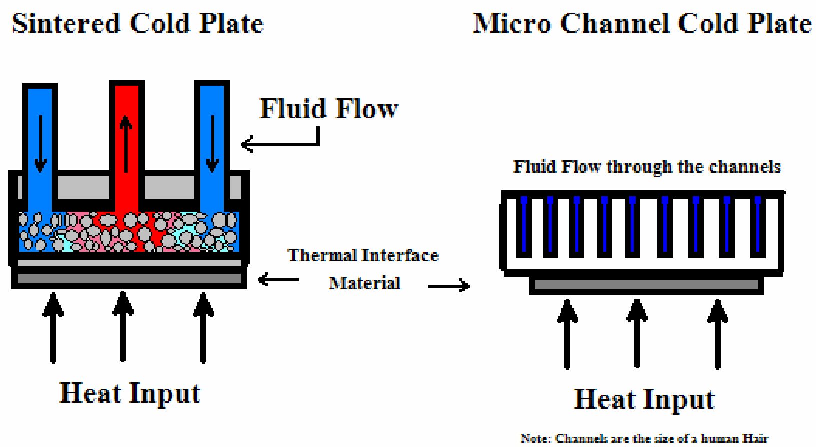

Figure 4. Sample Cold Plate Designs

Design Compromises

Nearly all thermal designs are a compromise between many conflicting parameters and requirements; space, costs, solution type, assembly effort, etc. These constraints limit cooling choices. Other constraints come into play beyond the usual concerns. In the case of the PPC970MP, the length of the Processor Interface (PI) bus can have an impact on the final cooling solution. The recommended maximum length of the PI bus that connects the microprocessor to the companion bridge part is 11 cm (5 in). Review the latest version of the datasheet for the most current values. The companion part will require its own thermal enhancement, which could constrain one or more of the lateral dimensions of the processor's heatsink.

The major operating environment constraints to be considered are; maximum cooling air temperature, speed of the airflow over the heatsink fins, direction of the air flowing over the heatsink, preheating the air by heat generating parts in the air stream, and air flow efficiently (is the air flowing through the heatsink vs. or just flowing above and around it. One item to consider is ducting airflow. Ducts can be used to direct airflow. Ducting can constrain the cooling air to flow through the heatsink vs. flowing around it.

Perhaps the next most important item to consider is the volume of space around the microprocessor for cooling. In the Server Blade example, this value is perhaps the biggest limit to heatsink performance where the height above the microprocessor is limited to less than 25mm. The volume around the processor is also limited due to the proximity of the companion chip. Mounting hardware could also impact the total volume for the heatsink.

70 Watt Thermal Design Example

A 'Server Blade' based paper design will be discussed below. These designs are based upon both a metal and vapor chamber type heat pipe based heatsink, see Figure 3. For this application, the processor's temperature is limited to 85°C. Note: The PPC970MP is specified to operate at 105°C. Finally, liquid cooling will be briefly discussed. This paper will not go into the details of the design process because they are heavily application dependent.

The first thermal design example is based upon a Thermacore™ vapor chamber, flat heat pipe, with dense fins. See Figure 3. In this case the heatsink is 5" X 5" X 1", airflow is 300 LFM with a maximum temperature of 55° C, fins are 0.016" thick with a 14 fin per inch spacing. Shin-Etsu high performance grease (6.0 watt/mK @ 0.002" bond line) is used as the thermal interface material. Flotherm™, a computational fluid dynamic package, was used to model this application and to determine the effectiveness of the solution.

Note: It is recommended to use a computational fluid dynamics (CFD) package to model the application and environment. The software package can be used to ensure optimal airflow over the heatsinks, locate airflow obstructions, hot spots, and to optimize the final cooling solution. The package should also be used to check that other parts are not being impacted by the warm air exiting the microprocessor's heatsinks or that other thermal problems are created.

Heat Pipe Example 1, PPC970MP, 70 watt dissipation.

In this particular case the thermal drops of the various components of the thermal path are:

- Maximum ambient cooling air temperature, 55°C.
- Thermal Interface thermal resistance and effective temperature drop: 6.8 °C for high end Shin-Etsu™ thermal grease (6.0 watts/mK @ 0.002" bond line.)
- 8 °C for moving the high heat flux into the vapor chamber of the Heatpipe.
- 16 °C rise form the heatsink to air.
- Calculated die temperature: 85.4°C.

With this model the processor's die temperature is approximately 85.4°C. This is just outside the desired range of the 85 °C modules.

Heat Pipe Example 2, PPC970MP, 70 watt dissipation:

- Maximum ambient cooling air temperature, 55°C.
- 4.8 °C for Arctic Silver 5™: Thermal Interface resistance and effective temperature drop
- 8 °C for moving the high heat flux into the vapor chamber of the Heatpipe.
- 11.7 °C rise from the heatsink to air
- airflow: 600lfm
- Calculated die temperature 79.5°C.

Using this model the processor's die temperature is held below 85°C, 79.5°C. Note: Artic Silver 5 thermal grease has a lower thermal resistance than the Shin-Etsu grease. Artic Silver 5 product may be electrically conductive where as the Shin-Etsu product is not. The decoupling capacitors found on the top of the 970MP package are connected to the power and ground planes. Keep the TIM material away from the decoupling capacitors.

Low Power Cooling Example

The second example to be examined is a fictitious ATX size evaluation board. The board will be using two PPC970MP processors each dissipating 28 watts maximum with a die temperature at 105°C. In order to attain the 28 watt dissipation level a slower part, lower clock rate, with a lower operating voltage is used. The expected operational conditions are; full power operating in a 45°C environment, use a fan-sink or forced air, 1.5m/s (300lfm), to cool the part. Several basic calculations must be made in order to get a basic size of the problem.

From the datasheet Θ_{JC} is 0.1 °C/W. The chosen thermal interface material has a thermal impedance of 0.08 cm² °C/W.

Following basic procedure:

a. The die temperature rise is 28W x 0.1°C/W= 2.8°C.
b. The temperature drop of the thermal interface material is: ((0.08 cm² °C/W) / area) x power, (0.08 cm² °C/W / 1.53 cm²) x 28W = 1.46°C == 1.5°C.

c. Thermal resistance of the heatsink. (Processor max temperature – thermal drop on processor – thermal drop of interface material – ambient air temperature) / power dissipation. Therefore: (105°C - 2.8°C - 1.5°C – 45°C) / 28W = 55.7°C/28 W = 1.98 °C/W
d. There are a wide variety of heatsinks that can meet the desired thermal resistance of the application.

Of course this is a first pass approximation of the final solution. The calculations do not account for obstructed or preheated airflow, manufacturing tolerances, altitude, or other problems. Generally, cooling solutions are 10 to 20 percent larger than absolutely needed in order to have reserve cooling capacity to account for manufacturing variability.

Several additional items need to be kept in mind:

A. Heat spread resistance: Is the heatsink base thick enough? Heat travels out of the processor die and into the heatsink. If the base plate is too thin heat has a difficult time spreading (spreading resistance) through out the heatsink. This will lead to a hot spot above the processor which could cause it to fail. Simplistically, base thickness varies according to the processors power dissipation level, higher power devices need thicker bases to allow the heat energy to spread up and out of the die and then to the fins.
B. How accurately is the thermal interface material applied? Note: First, review the manufacture's datasheet for the desired Thermal Interface Material thickness. Datasheets contain information allowing the calculation the relative thermal resistance of the interface according to thickness and heatsink mounting pressure. Generally, the greater the clamping force and or thinner bond line, the lower the thermal interface resistance:
    a. Greases need tight control over their thickness, thinner the better. Controlling the thickness of the interface material and pressure is key to maximizing its effectiveness. Thermal grease thickness (usually 0.025mm or 0.001 inches) can be more difficult to control than phase change materials.
    b. Phase change materials melt to fit. The heatsink needs some type of spring force to maintain claming force while the material melts into position.
    c. Heatsink to die clamping force: This covers two or three different areas; maintaining the proper claming force between the heatsink and processor die, maintaining the proper force between the PCB and heatsink, and limiting dynamic loads to the die.

Power Savings Modes, Power Tune, concerns

The PowerPC970MP microprocessors contain power savings modes that can affect power dissipation and performance. These power savings modes affect operating frequency and operating mode. The f/x power savings modes, f/2 or f/4**,** affect operating frequency of the processor. The nap, doze, and sleep modes greatly cut power, but affect performance (majority of operating units are not functioning). Review the microprocessor's User's Manual and Datasheet for detailed information on these power savings modes. The power savings modes can be used to cut power dissipation while maintaining some level of productivity. The modes can also be used to 'modulate' the power envelope of the application to given environmental or work load conditions. Power savings modes have many uses and should be investigated and used in power savings strategies.

Heatsink, Thermal Interface, and cooling resources:

Below is a small list of thermal product vendors. IBM does not endorse the use of these vendors. The list is present as a 'starter set' of vendors and their products.

Heatsink Vendors:
1. Thermacore International Inc. www.thermacore.com

2. Cooligy, Inc. www.cooligy.com, 2370 Charleston Road, Mountain View, CA 94043
3. Aavid Thermalloy Technologies, Inc., www.aavid.com

Thermal Interface material vendors:
1. Arctic-Silver TM, Arctic Silver Inc. 2230 W. Sunnyside Ave. Suite 6 Visalia, Ca 93277
2. Shin-Etsu, www.microsi.com/packaging/thermal_grease.htm or search on web for distributors.
3. Chomerics North America, www.chomerics.com, Parker Hannifin Corp., 77 Dragon Court, Woburn, MA 01801
4. Graftech International Ltd., www.graftech.com
5. Loctite thermal management products, http://www.loctite.com/int_henkel/loctite/index.cfm

Thermal Modeling: Computational Fluid Dynamics package vendors:
1. Flomerics Inc. www.flotherm.copm, 257 Turnpike Road, Suite 100, Southborough, MA, 01772
2. Fluent Inc., www.Icepack.com, ICE Worldwide Headquarters, 2700 Via Fortuna, Suite 301, Austin, TX, 78746

Pressure Indicating films:
1. Fuji Film: Pressurex™ Pressure Indicating Film, http://www.prescale.com/E/E.htm

Finally, the Internet is a tremendous source of information. Use the available search engines to find volumes of information on heatsinks, thermal modeling, interface materials, and vendor information.

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The IBM home page can be found at
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