IBM

Application Note
Thermal Considerations:
PPC970FX

Abstract

The 64-bit IBM PowerPC 970FX (PPC970FX) enters a new era of processing power and thermal dissipation over earlier PowerPC products. The processor can operate at multiple GHz clock speeds and can dissipate relatively high levels of power through a very small processor die. The high power dissipation levels of the high clock rate parts and small exposed area of the PPC970FX die dictate the need to carefully select the heatsink, thermal interface materials, and mounting methods for each intended application. The purpose of this application note is to inform the end user of the general steps that must be taken to properly design an appropriate thermal solution for the higher dissipation parts. The slower and lower power parts will not be discussed in depth in this application note. Designers should refer to the PPC970FX datasheet for specifics such as power dissipation, voltage, and packaging details for their specific application.

Introduction

The PowerPC 970FX can dissipate higher levels of power than the earlier PowerPC parts. This is especially true for the high frequency multi-gigahertz versions of the processors. The thermal issues occurring from the higher level of power dissipation (for example, an estimated 39 watts maximum for the 2.0 GHz, 105 C junction part) combined with the small size of the exposed flip-chip processor die (< 67 square millimeters) can be difficult to solve. Two different application environments and solutions will be discussed for the 2.0 GHz 39 watt version of the processor:

- The PPC970FX Evaluation board using a fan cooled heatsink
- A 1U server/router rack using conventional heatsinks

Note: This application note is to be used as a guide and not a solution for any given application. Many resources, heatsink vendor's engineering expertise and their application notes exist to aid in the eventual heatsink selection and mounting method. In general, heatsink vendors should be consulted to optimize the final thermal management solution.

Again, this application note will discuss the 2.0 GHz, 105 C maximum junction temperature (Tj), version of the PPC970FX with a maximum power dissipation of 39 watts. This is a large amount of power in a small die, (66mm^2). It is critical to remove the heat properly or the processor will fail. The following design issues must be solved when attempting this:

- Choosing heatsink technology for the given application
- Choosing the correct thermal interface material
- Developing the proper mounting hardware/methodology
- Correctly sizing the heatsink

Heat management solutions will be discussed for two target applications; the evaluation board using a standard fan cooled heat sink application for limited airflow and a heatpipe enhanced solution for the 1U rack application.

General Information

With the small die size the 970FX heat flux is approaching 60 watts per cm^2. This high power density requires that a detailed analysis of the environmental operating conditions of the processor be performed before selecting a heatsink product. Key to all heatsink selections is the flow rate and temperature of the air crossing the fins. In most applications of the higher powered versions of the PPC970FX require some

form of forced air to maintain proper operating conditions. To be certain that the heatsink environmental characteristics are adequate for a given application, it is suggested that some computational fluid dynamics package (for example, Flotherm™) be used to ensure proper thermal operations of the processor and to optimize the selected heatsink. Finally, working with quality heatsink vendors can reduce the design effort and testing process associated with heatsink selection.

Basic Thermal Transfer Theory

The first step to begin the heatsink selection process is to determine the operational environmental conditions and required heatsink thermal resistance (Rtot) budget needed for the given application. The environmental conditions are primarily ambient air temperature and air flow. Other parameters, air pressure, humidity, could be included in the evaluation process, but were omitted for this first pass at a heatsink solution

Using a simplified view (see Figure 1), the general junction to ambient resistance is the sum of three thermal resistance values: Rjc, Rcs, and Rsa.

Description of terms:

1. Rjc: junction-to-case. With the PPC970FX, the case is the exposed back of the processor die.
2. Rcs: case-to-heatsink. This is the thermal resistance defined by the thermal interface material and mounting pressure used.
3. Rsa: heatsink-to-ambient air. The general thermal resistance of the heatsink itself.
4. Rtot: junction-to-ambient. Total thermal path resistance.
5. Ta: Maximum ambient temperature of air that the heatsink will be exposed to.
6. Tj: Maximum junction temperature of the processor.
7. P: Maximum operational power dissipation of the selected PPC970FX part.

The total junction-to-ambient thermal resistance the processor will encounter is the sum of the three thermal resistance values:

$$Rtot = Rjc + Rcs + Rsa$$

This is also equal to:

$$Rtot = \frac{Tj - Ta}{P}$$

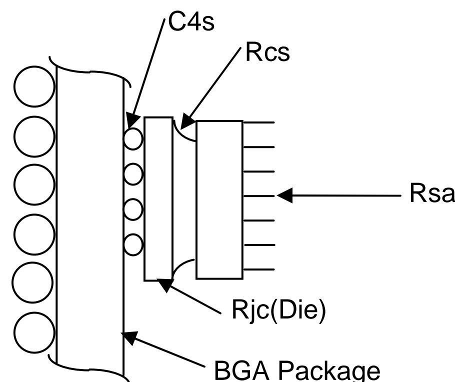


Figure 1. Thermal Resistance

The values for Rjc and P, can be found in the processor datasheet. Rjc is a fixed values and P is dependent upon several variables, primarily the processor speed, core and I/O voltages, and primarily the software application that is running. In the case of the PPC970FX, Tj is actually the maximum temperature of the internal thermal diode which is the specified maximum operating temperature of the part, i.e. 85°C or 105°C.

The heatsink/processor die interface resistance, (Rcs), depends upon the thermal interface material chosen for the application, pressure applied to the die/heatsink interface, and surface finish of the heatsink (planarity at the interface area). In general, the smallest attainable value of Rcs is best. This value is very difficult to directly specify because it can vary widely with mounting pressure, assembly quality, cleanliness of the contact area, and other parameters. The value can be inferred from the thermal interface material datasheet, but it must be understood that the resulting real value will be different due to the variations when mounting the heatsink to the processor module, the thickness of the interface material, the surface preparation, and other possible variables.

After reviewing the thermal resistance formula, note that the resulting value of Rtot is the maximum allowable thermal resistance of the processor-to-ambient environment. The formulas can be rearranged to show the maximum allowable thermal resistance of the heatsink for the given application.

$$Rsa = \frac{Tj - Ta}{P} - Rcs - Rjc$$

The chosen heatsink must have a thermal resistance less than this resulting value. Generally, the thermal resistance should be 15% to 25% less to make up for manufacturing tolerances and environmental discrepancies.

970FX Evaluation Board Application

The first application to be discussed is the 970FX evaluation board. The heatsink chosen was a fan-equipped heatsink. The evaluation board was designed to operate inside a ‘PC’ type case or exposed on the lab table or workbench. In either situation, the power dissipated cannot be removed with out airflow. This cannot be guaranteed inside of an off-the-shelf case, in the laboratory, or on the desktop.

As mentioned earlier, there are several constraints on the proper operation of the heatsink for this processor family, those being proper thermal interface material, reasonable heatsink size, smooth and planar mounting surface, and correct mounting procedures. A fairly large variety of heatsinks can be found that can eject this amount of heat, but these heatsinks will not work without using one of the best thermal interface materials available. Thermal transfer characteristics for older aluminum oxide heatsink pastes are too high and must not be used.

Note: The processor die rests upon a ceramic BGA carrier and some heat is dissipated via the carrier balls; however, because the thermal transfer resistance is more than 50 times higher than the die-to-heatsink thermal resistance, little power is dissipated by this path.

Choosing the Heatsink

For this application, various heatsinks and application notes from different manufactures were reviewed. Heatsink vendors were then consulted in order to derive an appropriate solution for the final product (the evaluation board), while at the same time offering some applicability for others. The heatsink chosen for this application is the CoolInnovations, Inc., 4-151508UBFA + Fan Assembly, (see Figure 2). This heatsink has a thermal resistance value of 0.75 C/W with a fan that moves 8 CFM. This capacity should allow the evaluation board to operate in all of the desired areas, PC case, lab, office, etc.

From the earlier formulas, the processor will remain within the safe thermal region with a maximum ambient temperature of 50°C and correct installation. Derating this value 10% results in a final value of 55°C. This should work well for the application where the board is in the ‘PC’ case and should ensure that the board will remain cool when exposed on the desktop, or in the lab.

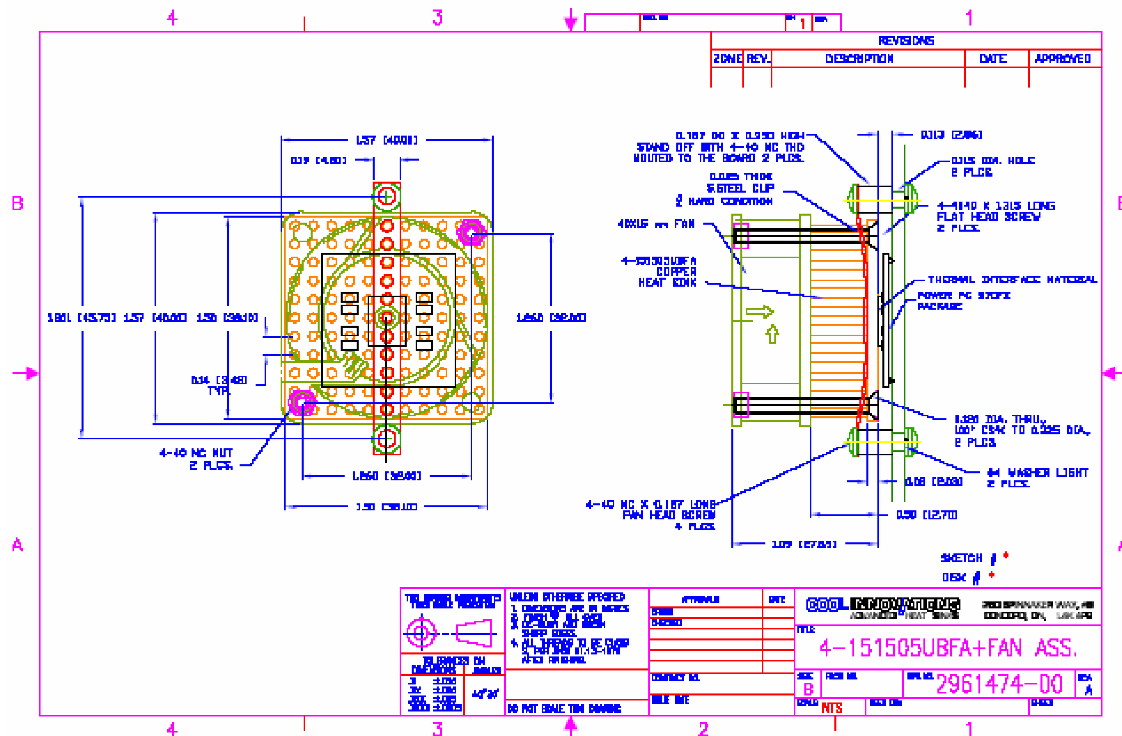


Figure 2. Cool Innovations Heatsink

Choosing the Thermal Interface Material

The thermal interface material to be used in any PPC970FX application is critical to the effectiveness of the total thermal solution. The interface material is used to enhance heat transfer by reducing thermal resistance across the processor die-to-heatsink interface. This also minimizes the variation of the interface resistance across the die surface. In general, older thermal pastes, pads, and glues do not do this effectively. Newer, superior thermal greases have been found that work well. An obstacle to be over come when using some these thermal interface materials is that some may be electrically conductive. Note: The processor has exposed decoupling capacitors on top of the ceramic package. When using these conductive materials, it must be carefully applied or it may short across the capacitors. Note: a ‘gasket’ could be applied to the processor’s body, shielding the decoupling capacitors from the heatsink and conductive thermal compound. The gasket would have a hole in it to allow the processor die to touch the heatsink directly and shield the capacitors.

Though not endorsed by IBM for fitness, the following list is a subset of high performance thermal interface material manufactures:

1. Artic Silver
2. Shin-Etsu

3. 3M
4. Dow Corning

NOTE: IBM does not warrant the fitness of a specific thermal interface material. It is up to the customer to determine the proper selection and use of thermal interface materials. The above-mentioned products are not the only appropriate thermal interface materials available.

Proper Heatsink Mounting

Because of the small size of the PPC970FX processor die and the CBGA package, the heatsink must be carefully attached and supported. Heatsinks designed to dissipate 40 watts are large and usually heavy. The maximum force allowed when mounting the heatsink to the die is 200psi. The area of the chip is 66mm^2 and results in a mounting force of approximately 20 pounds or 88 Newtons. Please refer to the latest PPC970FX datasheet for the latest mounting force values.

Note: If the processor's ceramic body is under-filled the mounting force can be increased by 50%. Refer to the white paper called Improving BGA to PCB Thermo-Mechanical Integrity for more information. It is up to the designer to test and approve the under-fill process.

The attachment method must be carefully designed for a given application. As can be seen from the mechanical drawing above (Figure 2), this evaluation board design uses spring clamp to hold the fansink to the processor. This will be adequate for the evaluation board, but probably will not work for other applications where shock, vibrations, and other environmental problems would be greater than in this example. Whatever the method used, the processor must be properly attached to the heatsink, and the applied force must be carefully controlled to prevent the CBGA or processor die from being damaged. The heatsink vendor should be able to suggest several different mounting methods.

Conclusion

A fan-cooled heatsink was chosen for the evaluation board application. The processors will be cooled whether the board is in a 'PC' case or exposed in the lab. The heatsink can only do its job if the proper thermal interface compound is chosen and applied correctly, the proper mounting pressure is applied and maintained, and the board is not exposed to excessive vibration or shock.

1U Rack Application

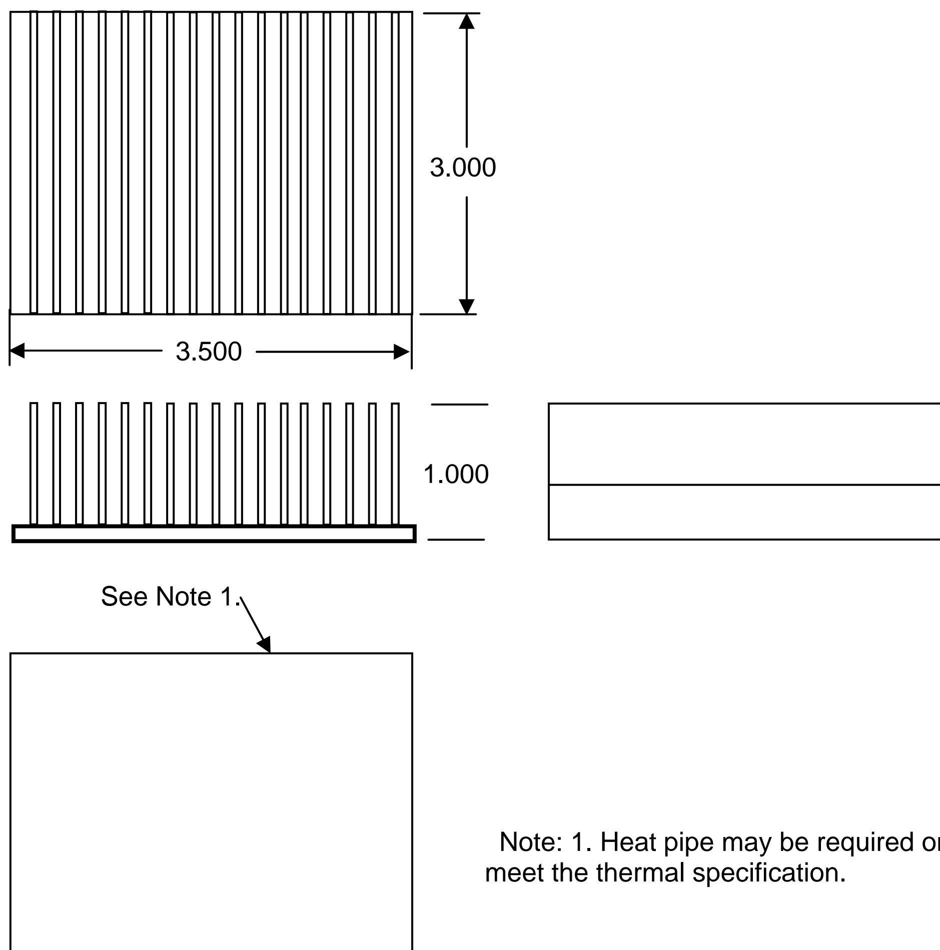
The second application to be discussed is one for the 1U Server/Router rack space using forced air. In this application airflow is at 400 LFM with a maximum ambient of 55 C. The application is aimed at the router/server application space. In this application the PCB and heatsink will be height-space constrained. The 1U rack space allows 25mm of height for the heatsink and 3mm separation between the top of the heatsink and case. Two general heatsink solutions will be presented, an aluminum heat pipe augmented heat sink and a copper base aluminum finned heatsink. Both heatsink solutions have been modeled using a computational fluid dynamics software package to arrive at the final thermal resistance values. In addition, the effects of ducting cooling airflow will be briefly discussed.

The 970FX power levels in this form factor present a challenging thermal design. As mentioned earlier, there are several constraints on the proper operation of the heatsink for this processor family, proper thermal interface material, quality heatsinks, and correct mounting procedures. Mounting procedures will only briefly discussed because of the broad variety of possible mounting methods.

The heatsinks modeled in this application (copper base aluminum finned and heat pipe enhanced aluminum) are the same size, 89mm x 76mm x 25 high with dense fins. Note: The final heatsink size was determined after including an air duct to direct air flow through the device.In general, both heatsinks performed similarly. The heatpipe-augmented heatsink's thermal resistance is approximately 5% higher than that of the copper base heatsink, which is within the error of the model.

Table 1. General 1U Heatsink Parameters and Modeling Results

Heatsink Type	Duct Width mm	Heatsink Temp C	Case Temp 0.03C in^2/W	Delta T Sink to Ambient C	Thermal Resistance C/W	Weight g
Copper Based Aluminum Finned	190	80.7	91.9	25.7	0.643	327
Heatpipe Based Aluminum	190	81.9	93.1	26.9	0.673	163
Copper Based Aluminum Finned	114	76.7	87.9	21.7	0.543	327
Heatpipe based Aluminum	114	77.9	89.1	22.9	0.573	163



Note: 1. Heat pipe may be required on this surface to meet the thermal specification.

The primary difference between the two heatsinks is weight and cost. The copper heatsink has twice the mass of the heat pipe-augmented heatsink. The weight difference between the heatsinks can lead to problems mounting the part and meeting the packaging and mounting specifications. The Heatpipe based solution is a higher cost item.

Optimizing Heatsink Selection

One way to enhance the cooling capability of a heatsink and reduce its size and mass is to duct the cooling airflow through it. Airflow is directed to flow along the fin axis of the heatsink. When using a duct, cooling air is constrained to flow around and through the heatsink instead of flowing inefficiently around, over, and by the heatsink and fins. According to the analysis performed, ducting could result in an apparent 10 to 15% reduction of the heatsinks thermal resistance value. The effects of ducting should be modeled to derive results for a particular application. Figure 3 details the basic size of the two heatsinks and the effects of ducting the airflow. The effective thermal resistance values in Table 1 were derived from the general heatsink design in Figure 3, and the numbers for ducting are also given for a 190mm wide duct and a 114 mm wide duct. The values for an unducted module were not generated but can be derived from earlier information.

Heatsink Mounting Information

Heat sink mounting information will not be discussed in detail for this application. Basically, the heatsink could be mounted to the PCB with spring loaded posts and supporting brackets, or mounted to an enclosing clam shell type of case with pressure applied to the back of the PCB forcing the processor on to the heatsink. The mounting method must be reviewed with the heatsink vendor to ensure it will perform as expected.

Additional Processor Information

Please refer to the PPC970FX processor datasheet for the latest detailed power dissipation, mounting information, and mechanical values. Always make sure that the latest datasheet is being referenced.

Detailed PPC970FX Thermal Modeling Information

In order to build a fluid dynamic computational model for the PPC970FX chip, the following information is usually needed. The general PPC970FX package specifications can be found in the PPC970FX datasheet.

The following information can be used to develop the computational fluid dynamic information.

PPC970FX mechanical information

1. Package Substrate
    a. Package length 25mm
    b. Package Width 25mm
    c. Package thickness1.2mm

2. Die Dimensions
    a. Power Dissipation depends upon the processor selected
    b. Die Length 7.4mm
    c. Die Width 9.55mm
    d. Die thickness 0.785mm

3.Flip Chip Bumps

a. Number of bumps in x direction 33
b. Number of bumps in y direction 44
c. This is a regular array
d. C4 Bump Diameter 0.008mm
e. C4 Bump Height 0.00808mm
f. C4 Solder Material Solder (Sn96: Pb 04)[1]
g. Underfill Ablestik 8360

4. Bottom of Package Solder Balls

a. Balls in X direction 24
b. Balls in Y direction 24
c. Ball Diameter 0.8mm
d. Ball Pitch 1 mm.
e. Substrate Standoff 0.81mm
f. Ball Solder Material Solder (Sn63, Pb 27)[1]

Conclusions

Choosing a heatsink for the PPC970FX can be serious undertaking for the higher power parts. The processor higher frequency [arts can dissipate nearly 70 watts. The flip chip processor die is very small (66mm^2), and the die is mounted upon a ceramic chip carrier. To ensure system reliability, heatsink and thermal interface materials must be investigated and chosen for the given application and environment. Additionally, another design consideration is the heatsink-to-PPC970FX package mounting method. This is application/environment dependent. Finally, it cannot be overstated; working with a competent heatsink vendor can help to ensure success with the final heatsink design.

Thermal Interface and Heatsink Vendors

The following list is a subset of thermal interface and heatsink suppliers. Additional information can be found with other vendors.

1. Cool Innovations Inc., www.coolinnovations.com
2. The author would like to thank the engineers at Thermacore Inc. for their modeling of the 1U rack space example. Thermacore International Inc. www.thermacore.com
3. Artic-Silver TM, Artic Silver Inc. 2230 W. Sunnyside Ave. Suite 6 Visalia, Ca 93277
4. Shin-Etsu, www.shinetsu.jp.co or search on web for distributors.
5. Avvid Thermal Technologies, Inc., www.aavid.com

[1] Future version of the PPC970FX processor will be built using a lead free solder. Please check data sheet for more information.

Revision Log

Revision Date	Contents of Modification
1-19-03	Created preliminary draft.
2-12-04	Second release.
2-25-04	Changed Figure 1. Thermal Resistance.
2-27-04	Made small changes to text.
07-20-05	Update text and remove IBM Confidential from document.

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