Concurrent Design of a PowerPC™ Microcomputer: EDA and CFD Tool Interoperability

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Abstract

This paper discusses an attempt to begin thermal analysis at the inception of the printed-circuit board design process, when designing a microprocessor-based desktop system. The goal was to assess a methodology that should help to define a real concurrent design process for future projects. We emphasize here the thermal aspects of this concurrent process that required the use of a board-level (within the electronic-design automation (EDA) environment) and a system-level thermal analysis tool (computational-fluid dynamics (CFD)).

After describing the project, and the dataflow currently available between the EDA and the CFD tool, we describe the practical steps that were carried out in this project, and how thermal design constraints may be applied, during the component placement phase of the printed-circuit board design. Overall the experience gained through this project on multi-level thermal analysis, as well as, working in a cross-functional team environment is presented. Also presented are the steps for implementing such a concurrent design flow.

Introduction

Electronic system performance has dramatically improved over the past three decades. Much of this improvement is a result of the increased integration of components at the semiconductor level made possible by reduced feature sizes. The level of integration now possible at the chip level has resulted in several semiconductor integrated-circuit (IC) trends, all of which are increasing: gate count, chip inputs/outputs, chip size, operating frequency, and power consumption. All these trends have resulted in increasing thermal flux at the chip level. Furthermore at the package level, there is a continuing trend of packaging chips in an ever decreasing footprint and volume. Together with the increasing use of surface-mount technology and expanding use of ball-grid array and "chip scale" packages, these trends have resulted in higher power dissipation at the board-level. On the system-level, as seen with recent development of desktop, laptop and palmtop systems, more features are being placed into a shrinking enclosure with less and less air and space available for designing a thermal management scheme. Thermal control of microelectronic devices is required for proper operation and acceptable reliability and is becoming an increasingly critical part of the design of microelectronic systems [Lasance,1995].

Today's electronic systems require a very diverse set of requirements that must be met by the electrical, thermal, mechanical, and packaging engineers. Various computer simulation tools are being used to predict the physics of these class of problems. The interoperability of such computer simulation tools, by reducing the design- and analysis-cycle time, offers a potential reduction in the product development cycle times, while reducing potential pre-processing errors. This paper presents the concurrent design process methodology within the printed-circuit board (PCB) layout and the thermal system simulation for a desktop microcomputer. We will discuss the interoperability between an electronic-design automation (EDA) tool [Mentor Graphics, 1996] and a computational-fluid dynamics (CFD) tool [Flomerics, 1995] to complete the thermal analysis of a microcomputer system. More specifically we will describe data flow and the model simulation results within the electronic-design automation (EDA) and the computational-fluid dynamics (CFD) tool environment for a PowerPC 603 and PowerPC 604 microprocessor-based desktop system.

Assessing Concurrent Design and Analysis: Board- and System-level

Performing thermal analysis at the inception of the PCB design process flow may be a condition of overall product success (Figure 1). It obliges the entire team to work together; that is, the electrical, mechanical, and packaging engineers working hand-in-hand with the layout team to translate and integrate the primary physical constraints of the design. The assessment of the product design flow can really be achieved with the interoperability of design tools, specifically for thermal analysis. Board layout and component libraries provide a way to automatically create a PCB thermal model, which can be then easily transferred, after simplifications, into a system-level simulation tool. Then the system-level tool computes the heat transfer condition around the PCB. It provides detailed heat transfer information around the PCB and the components that can be transferred to the PCB thermal tool to perform the analysis on the fully populated board.

Using thermal analysis tools, thermal engineers can ensure that system's thermal requirements are being adequately addressed before the PCB is fabricated. Some other key advantages are:

- Reduce product development cycle time by performing the analysis during the design phase, not after.
- Improved thermal prediction techniques.
- Using the EDA database does not require the thermal analyst to pre-process component geometry's, powers and locations; thereby, improving the accuracy of the model and reduce cycle time.
- Numerically parametric studies of thermal enhancement features: from PCB conductivity to fan performance.
- Board-level simulation; interaction, thermal loading of adjacent components.
- System-level simulation shows the impact of card placement, fan location, etc.

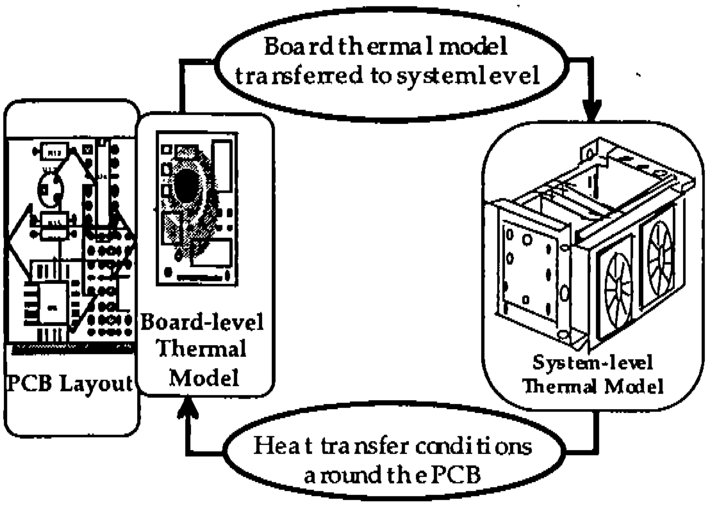


Figure 1. Interoperability of thermal board-level and system-level analyses

PowerPC Common Hardware Reference Platform Desktop Microcomputer

The scaleable PowerPC™ Reduced-Instruction-Set-Computer (RISC) architecture microprocessor family jointly developed by Apple, IBM, and Motorola, is being designed into high-performance cost-effective computers (including notebooks, desktops, workstations, and servers). The PowerPC microprocessor family includes: the PowerPC 601™, PowerPC 602™, PowerPC 603™, PowerPC 603e™, PowerPC 604™, PowerPC 604e™, and the PowerPC 620™ microprocessor [Kromann et al, 1995], [Gerke et al, 1995], [Kromann, 1996]. Each microprocessor is designed to meet the needs of a different segment of the marketplace.

The microcomputer system investigated in this study is a PowerPC Common Hardware Reference Platform (CHRP) compliant reference system (code named "Yellowknife") [MOTOROLA, 1996c]. The Yellowknife design is a uniprocessor system that accepts either the PowerPC 603 or the PowerPC 604 microprocessor. Yellowknife supports all 2.5V and 3.3V PowerPC 603 or the PowerPC 604 microprocessor operating in modes which result in external processor bus speeds up to 66 MHz. The maximum power dissipation of the PowerPC 604 microprocessor is 22 watts [Motorola, 1995a]. Voltage regulators will be placed on the PCB to provide voltage requirements for different microprocessors. The microprocessors are packaged in controlled-collapse-chip-connection/ceramic-ball-grid-array (C4/CBGA) technology [Kromann]. Each C4/CBGA is then mounted to an interposer, used to convert the ball-grid-array (BGA) footprint to the pin-grid-array (PGA) footprint.

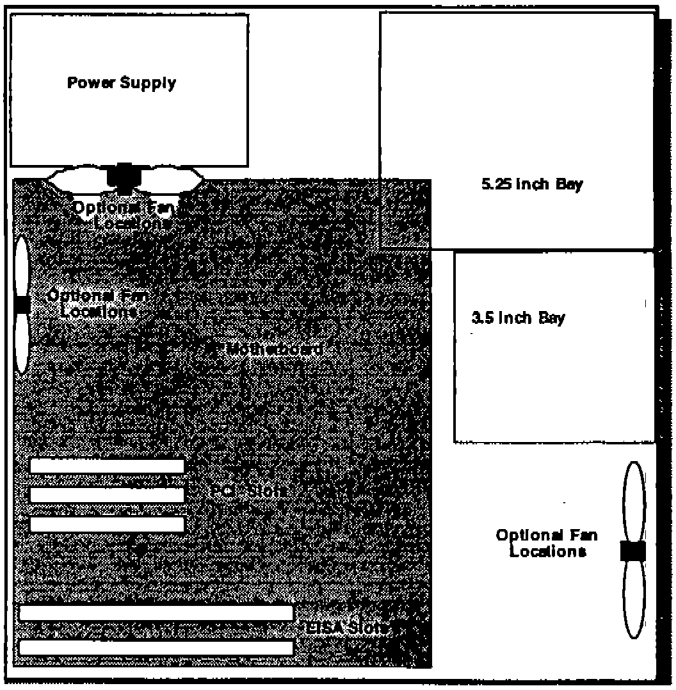


Figure 2. Salient Features of the motherboard and chassis (side view).

The Yellowknife chassis uses an industry-standard form-factor chassis and supports a total of five I/O slots for add-in cards (Figures 2,4). Three of the slots support PCI cards and the remaining two support ISA cards. The memory subsystem comprises in particular a DRAM expandable 64-bit memory bank , allowing to support up to 132 MB. The system is made of up to 4 SIMM cards (Single-In-line Memory Module) each of them dissipating approximately 5 watts.

The Yellowknife chassis Drive Bays has two external 5.25" drive bays and two internal 3.5" drive bays. This combination of available drive bays allows systems to be built in configurations such as the following that will be used for the initial systems assembled: 1) one IDE hard drive, 2) one SCSI hard drive, 3) one 3.5" floppy drive, and 4) one CD-ROM drive. Other configurations are clearly possible, including support for an external tape drive and/or a third hard drive.

Numerical Thermal Simulation: Printed-circuit Board Level

A preliminary component placement was determined that met the design requirements of a cross-functional design team, concurrent with the product requirements. The next step was to complete board-level and system-level thermal simulations for complete thermal validation <u>before PCB routing</u>, which was recognized as the critical goal to achieve. In concert with the electrical engineering team an initial placement was considered for the key components. Then PCB placement began.

This first simulation run exposed the components that greatly exceed the manufactures recommended operating temperatures. These components are identified as requiring additional heat sinking solutions and/or relocation candidates (however, relocation decisions were made as a team, as there may be other electrical issues (e.g. timing, signal integrity). From the initial component placement, the following were the key components that were identified as potentially requiring thermal enhancements: microprocessor, 4 FETS, SCSI controller, an ASIC, Cache Tag and Clock Driver (Figure 3). The following gives examples of steps that were taken.

<u>Microprocessor</u> : will require an active or passive heatsink and lets try to place in an area that will not get shadowed. Also, within the layout tool, geometry constraints were defined in an area around the CPU.

<u>FETs</u> : the four FETS initially were placed very close together in a quad arrangement. Simulation showed that by spreading these components out or placing them in an in-line arrangement would reduce the temperature rise by approximately 20%. In addition, another simulation run showed the local enhancement of PCB conductivity could further reduce the die-junction temperatures by approximately 5 to 10%.

<u>Cache Tag</u> : its location was critically placed near the microprocessor, for routing and signal integrity/crosswalk issues. However, it was placed away from the microprocessor in case a heat sink was required.

Numerical Thermal Simulation: System-level

The CFD model of the chassis is composed of the following main elements: 1) the Outer Case and Internal Structure; 2) the Power Supply Unit (PSU); 3) the PSU Fan; and 4) the Disk Drives & Ancillaries.

<u>Outer Case and Internal Structure</u> The outer case of the computer consists of a series of plastic sheets lined with thin metal plates. In this arrangement there is a thin layer of air trapped between the metal and the plastic cutting and, therefore, the case is almost adiabatic. It is modeled in CFD tool using <u>*External Walls*</u> with a conductivity derived from the thermal resistances of the metal sheets, the air gap and the plastic wall in series.

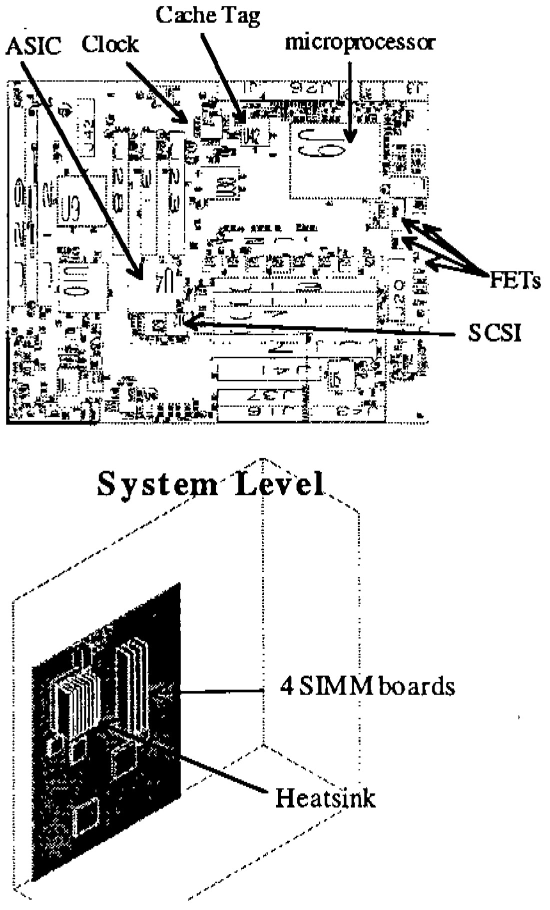


Figure 3. Fully Populated PCB in board-level thermal tool, after transfer from layout, is then simplified and transferred into system level (SIMMs and heatsink on the processor have been added at this point).

In this simulation, radiation from the outside of the case has been omitted in order to arrive at a conservative answer. The perforations and slots in the case are modeled as <u>*Vents*</u> with the Loss Factor set to 1.7 (based on Device - [Flomerics,1], [Flomerics,2]). This estimate of loss factor is expected to be adequate for a first analysis although, should the thermal design prove to be marginal, a more detailed assessment of the pressure loss through the vents would be carried out.

The internal metal structure used to support the disk drives and ancillaries (for example, tape drive and CDROM) is modeled using <u>*Internal Plates*</u>. In doing this, we are assuming that the heat conduction within the fabric of the structure is not ignificant and that the heat dissipated by the disk drives and ancillaries is convected away in the cooling flow. This is, again, expected to give a conservative answer for the motherboard thermal analysis. It should, however, be noted that for some heavily equipped configurations (typically PC's acting as servers), the cooling of the drives and the drive bays may in fact be a more pressing problem than the motherboard and processor(s).

Power Supply Unit (PSU)

The modeling of the PSU and its associated fan (see next section) presents the most difficult part of creating and validating this chassis model. There are a number of factors which need to be addressed: 1) the pressure drop characteristics of the PSU; 2) the effect of component proximity on the fan haracteristic; and 3) power dissipation of the PSU and PSU fan.

The main problem for a designer addressing these problems are practical issues because he/she has little control over which PSU is used. In particular: 1) manufacturing departments may change the installed unit to save cost; 2) the PSU manufacturer might change the internal layout of components; or 3) the end user may install his/her own PSU as a replacement part.

And, whilst the mechanical form factor and electrical specification may be the same, there is usually no attention paid to thermal specification. With the PSU being an integral part of he thermal design of this type of chassis, thermo-fluid compatibility becomes increasingly important.

There are two approaches that can be taken: 1) At the preliminary design stage, the designer has little choice but to use correlations based on the expected component packing density and test for the sensitivity of the design to the assumed values. Correlations that might be useful can be found in texts such as [Perry & Chiltern], [Fried & Idelchick], [Flomerics, 3]. 2) Once a PSU has been specified (or if a module of similar configuration is available), a bench test can be carried out to determine the flow rate for the unit under conditions with no back pressure. The PSU manufacturer may also be able to supply this data. Unfortunately, this cannot simply be assumed to be the flow rate through the system since the unit will also see a back pressure due to other elements in the system.

In the analysis reported in this paper where we have no data on the performance of the PSU, we have chosen to apply a pressure loss coefficient of 40m^{-1} (i.e. 40 dynamic heads per meter of length) which is based on a rough assessment of the likely component packing density of the PSU. When assessing the final results, considerable attention would be paid to the effect of varying this parameter within practical limits and this might result in design constraints being placed on the PSU vendor.

Power Supply Unit (PSU) Fan

The physical structure of the PSU fan was modeled using a ombination of *Internal Plates* and a *Cuboid Block* to create an annular duct. The fan characteristic is taken as a straight line approximation to the supplied fan curve in the region of the operating point. This level of detail is more than adequate for a fan drawing configuration but might need additional detail for the fan blowing configurations [Flomerics, 4].

Assessing the effect of swirl in blowing configuration is a further difficulty. Modeling swirl in CFD tool is not very difficult, simply involving the use of a number of *Volume Sources*. However, there are considerable problems in obtaining the data from fan manufacturers in the first place. This parameter is rarely (if ever) measured and, furthermore, varies with the operating point of the fan. For the Yellowknife configuration, a ratio of order 0.7 of the swirl to axial velocity was used.

Disk Drives & Ancillaries

For the designer of a chassis such as this, the modeling of disk drives and similar ancillaries (for example, CDROM and tape drives) represents a further complication. Once again, the issue is one of control. Although the initial design may assume a certain configuration, the end-user of the system may choose a totally different configuration and/or the drive manufacturer may change the specification.

Fortunately, the coupling between the thermal behavior of the drives and the motherboard is far weaker than the coupling between the motherboard and the PSU. Therefore, in the absence of better data, modeling the ancillaries as *Cuboid Blocks* of appropriate conductivity with a pessimistic estimate of power dissipation represents an acceptable solution for an engineer struggling to meet design deadlines. In the analysis described here, blocks of conductivity 50 W/mK have been used. The value of 50, although seemingly arbitrary, is a reasonable guess given the high metal content of a typical disk drive assembly. We are also assuming a worst case scenario where little heat is conducted into the fabric of the chassis (through the plates). Under these circumstances, the air side heat transfer coefficient dominates and the actual value of conductivity chosen is secondary.

Motherboard

After simplifying the motherboard in the board-level EDA thermal tool, it was translated into CFD tool as a 3D assembly of cuboids. During the first analyses, of the remaining components, the components dissipating at least 1 W were sent to CFD tool. In that case, the remaining power is distributed in the PCB, ensuring that the overall heat load is consistent between the two models. At this point, the components were transferred with the default conductivity of 10 W/mK, while the PCB had a conductivity of around 19 W/mK.

EDA and CFD Tool Interoperability Results

While performing board-level thermal analyses using system-level CFD results, the question of the consistency of the models between board-level EDA thermal tool and CFD tool came up several times. Being in an on-going design process on the board side, we have to use the same boundary conditions from CFD tool for several options for the board. In that case, it may be important to know when it is necessary to go back to CFD tool with an updated board models, and which risks of important inconsistencies may be taken during this "creative" step of the board design process. Note, the following results were obtained with the fan drawing air from the enclosure through the power supply unit (PSU).

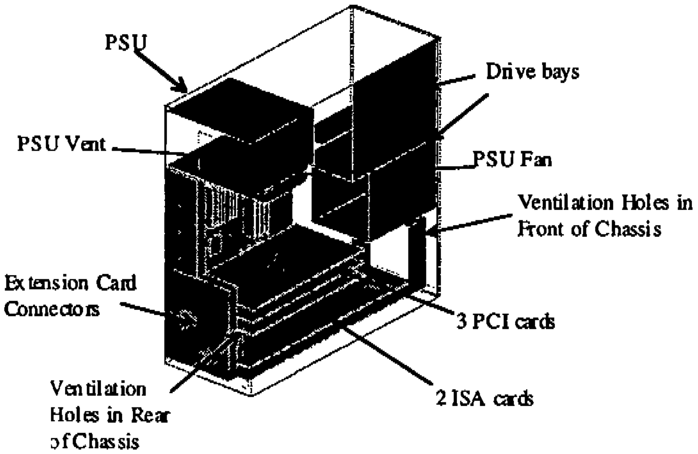


Figure 4 . Model of the ATX chassis

The configuration with the power supply fan only is presented here. Detailed system-level analysis can be conducted, analyzing the merits of a the fan in blowing (figure 5) or xhausting configuration. Detailed flow information like the influence of the fan swirl on the heatsink performance can be analyzed, and corrective action can be taken if necessary.

Figure 6 shows that the cooling of the processor, in the fan blowing configuration, the heatsink is heavily influenced by the spreading of the air from the PSU fan. This tells us that modeling the swirl from the fan is important in this case since it influences the spreading through centrifugal action.

Figure 6 shows also how changing the direction of flow of the fan results in a flow that is far more even through the processor heatsink. One of the benefits that is often sought when using an exhaust fan configuration is improved airflow through vents in the casing. An exhaust fan creates a negative pressure (relative to the atmosphere) inside the case which tends to result in more even flow through the case vents (see, for example, Reference [FLOMERICS]). But in this particular case, due certainly to the other geometrical features of this enclosure, the overall performance of the processor heatsink was found to be degraded by about 6 C.

For each system level situation, it is possible to extract the local heat transfer conditions on the board, including the performance of the heatsink as simulated within the system. This data is then used for detailed board-level analysis with the board-level tool, and to analyze for example, the impact of the dissipation of the SIMMs board on the components closest to them (just above them in figure 7). These components see their junction temperature rising from a range of 54 to 64 C to a range of 65 to 92 C. This clearly demonstrates how the reliability of otherwise low-powered components (around 17 mW in this case) can be impacted by the overall environment.

Summary

For any electronic product, achieving a first-pass success is far more likely if the thermal analyses are concurrent with the product design-cycle phase. It is then important to incorporate thermal management at the earliest possible stage, or else you run the risk of thermal issues delaying the entire project. Using thermal analysis tools, the design teams can ensure that system's thermal requirements are being adequately addressed before the PCB is fabricated. This results in shorter product development times, without compromising product quality, while, reducing time-to-market and lowering overall product costs.

Interoperability between layout, board-level thermal analysis and system-level thermal analysis is now available. The electronic companies have the tools needed to redefine their overall PCB design process, bringing thermal analysis into this process. With the increasing complexity of boards, board-level thermal analysis has to be linked tighter with the layout tools, to answer for example questions like : "if I need to implement thermal enhancements to cool this component, is the board still routable?" But with the shrinking of the enclosure in which these boards have to fit, it is imperative to bring system-level thermal constraints into the EDA environment.

In the future, it is expected that the various analyses needed for evaluating PCBs will be part of the front-end of the design process [Seaton, 1996], [Maliniak, 1994], [Strange, and Suaris, 1995]. These tools will help the designers to define the product performance requirements, and also to translate these requirements into constraints for further automation of the design itself. They will also be used to interactively assist the designer in making design decision on the fly, or get back to the specialist if required. The implementation of these tools will still rely on well established design process flows that can be tested and implemented with the tools available today.

Bringing successfully analyses tools into the PCB design process means that these tools may be used on-the-fly by a non-specialist. It may be achieved for example for thermal analysis if the model creation can be automated, using in particular component model libraries and reliable boundary conditions from a system level thermal. The creation and the validation of this data remains the domain of the specialist, working in parallel on different projects, within cross-functional teams.

By successfully applying the design and analysis methodology presented is this paper, the first Yellowknife systems were fully operational and all components were within manufacture's recommended operating temperatures. In addition, for room temperature environmental operational conditions, the microprocessor, was the only component requiring a heat sink. Future work is ongoing to conduct an experimental program to quantitatively compare with the numerical results presented here. Other parametric studies may be considered to the inlet/exhaust enclosure fans arrangements and an active/passive microprocessor heat sink.

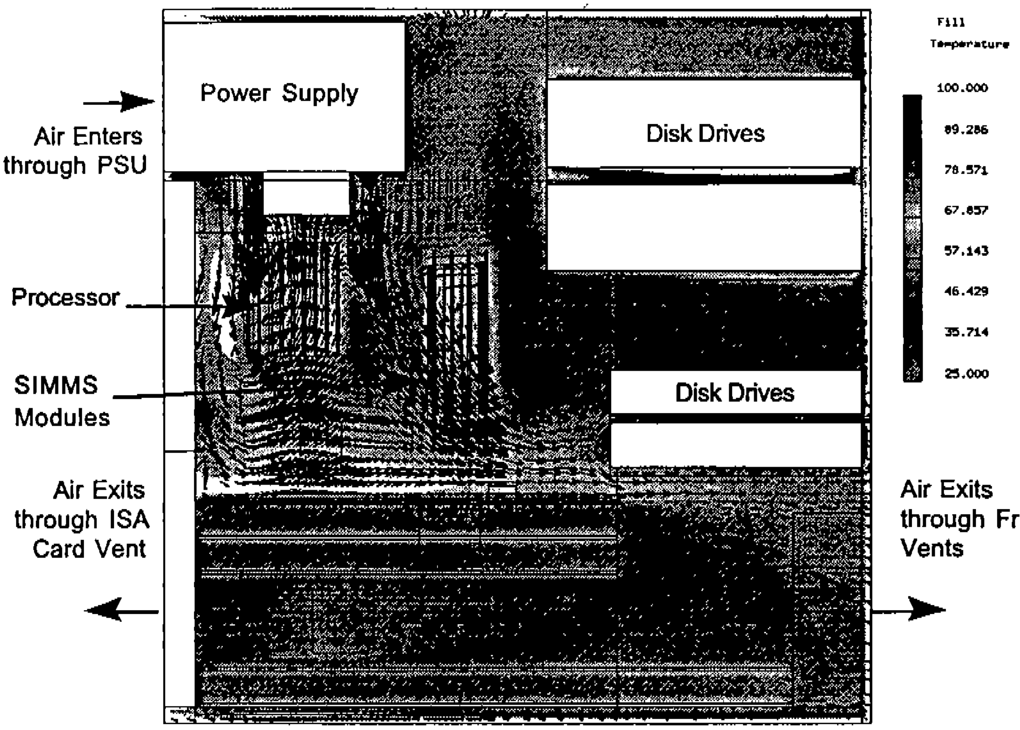
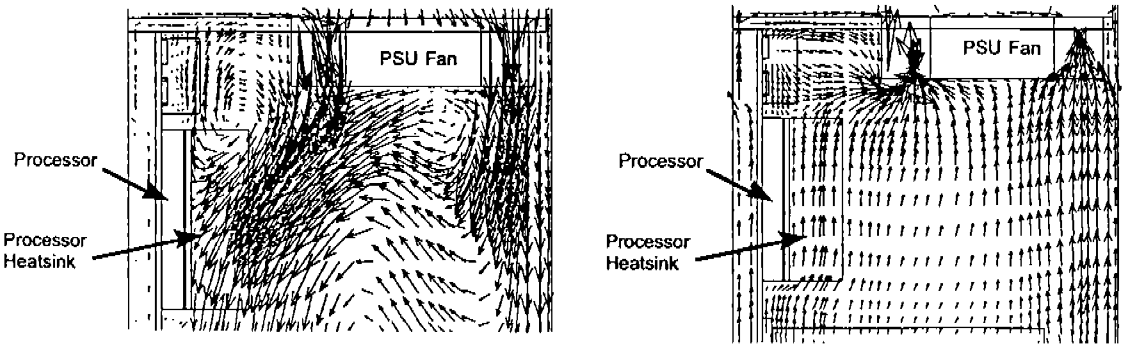


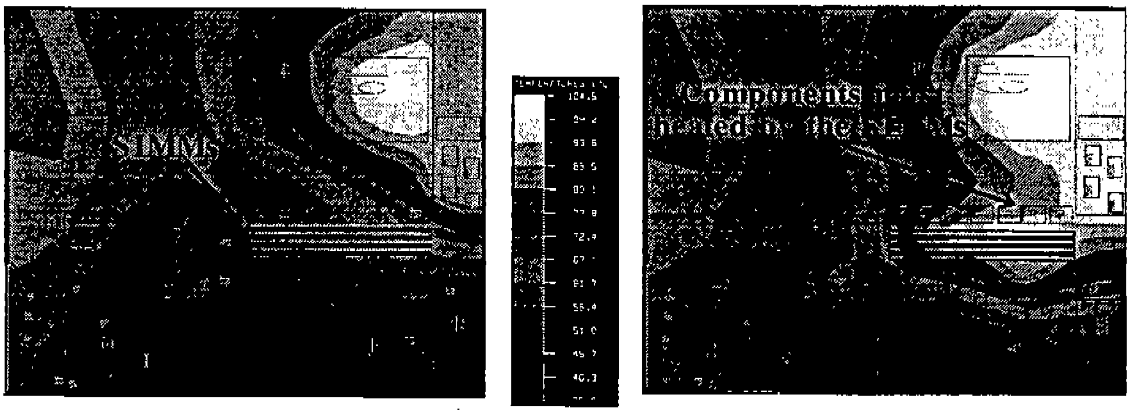
Figure 5 Results for the fan blowing configuration. (Temperature on a plane through the processor heatsink Velocity vectors on a plane through center of the PSU fan)



(a)

(b)

Figure 6. Processor heatsink performance with fan blowing (a) and exhausting (b)
Close-up of flows through the processor heatsink



(a) 4 x 1 watt **(b) 4 x 5 watt**

Figure 7 : Influence of the power of the SIMMs on the mother board

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REFERENCES

ADDISON, S., and PIMONT, V., "Bringing Thermal Analysis in the PCB Design Cycle"; PCB Design Conf., PCB Thermal Design Seminar, Santa Clara, March 18-19, 1997

ANDREWS, J., 1988, "Package Thermal Resistance Model Dependency on Equipment Design", IEEE Components, Hybrids, and Manufacturing Technology, vol. 11, No. 4, pp. 528-537.

FLOMERICS, 1995, FLOTHERM User's Manual.

FLOMERICS,1, http://www.flomerics.com/tips/flow_res/flow_res.htm

FLOMERICS,2, "Specifying Flow Resistances"; FLOTHERM User News; March 1995.

FLOMERICS,3, FLOTHERM Advanced Training Course: Lecture II - Uses of Resistances; 28 April 1993.

FLOMERICS,4, http://www.flomerics.com/desktop/desktop.htm

FLOMERICS,5, "Don't Be So Attached to Your Fan Curve", FLOTHERM User News; August 1995.

FLOMERICS,6, FLOTHERM Lecture Course Notes; pV-6 Fans with Swirl; Ref : FLOTHERM/LC/0993/1/0.

FRIED & IDELCHICK, "Flow Resistance - A Design Guide for Engineers" ; publ. Hemisphere.

GERKE, R.D., and KROMANN, Gary, 1995, The Effect of Solder-joint Temperature Rise on Ceramic-Ball-Grid Array to Board Interconnection Reliability: Motorola PowerPC 603™ and PowerPC 604™ Microprocessors and MPC 105 Bridge/Memory Controller,ASME/JSME INTERpack-95, March 1995. (Also available from Motorola's PowerPC website: http://www.mot.com/powerpc/)KROMANN, Gary, et al 1995, Motorola's PowerPC 603™ and PowerPC 604™ C4/Ceramic-Ball-Grid Array: The Motorola PowerPC 603™ and PowerPC 604™ RISC Microprocessors, INTERpack-95, March 1995. (Also available from Motorola's PowerPC website: http://www.mot.com/powerpc/)

KROMANN, Gary, 1996, Thermal Management of a RISC Microprocessor, the C4/Ceramic-ball-grid Array Interconnect Technology, Proceedings of the 45th Electronic Components & Technology Conf., May 1995. (Also available from Motorola's PowerPC website: http://www.mot.com/powerpc/)

LASANCE, C., 1995, The need for a Change in Thermal Design Philosophy, Electronics Cooling, Volume 1, no.2, pp24-26

LIN, P.C. and NQUYEN, L.I., 1993, Thermal Characteristics of IC Packages, EUROTHERM Seminar 29, Delft, The Netherlands, 14-16 June 1993.

MALINIAK, L., 1994, Nix physical design flaws before layout, *Electronic Design*, May 1994.

MENTOR GRAPHICS, 1996, AutoTherm User's Manual.

MOTOROLA, 1994, PowerPC 603 RISC Microprocessor User's Manual, IBM/Motorola.

MOTOROLA, 1995a, PowerPC 604 RISC Microprocessor Hardware Specifications, Motorola. (Also available from Motorola's PowerPC website: http://www.mot.com/powerpc/)

MOTOROLA, 1996a, PowerPC 603e RISC Microprocessor Hardware Specifications, Motorola. (Also available from Motorola's PowerPC website: http://www.mot.com/powerpc/)

MOTOROLA, 1996b, PowerPC 604e RISC Microprocessor Hardware Specifications, Motorola. (Also available from Motorola's PowerPC website: http://www.mot.com/powerpc/)

MOTOROLA, 1996c, PowerPC Platform: Yellowknife System Design Guide, Motorola. (Also available from Motorola's PowerPC website: http://www.mot.com/powerpc/)

PERRY & CHILTERN, Eds, "Chemical Engineer's Handbook".

ROSTEN, H., 1996, "DELPHI - A Status Report on the European-funded Project for the Development of Libraries and Physical Models for an Integrated Design Environment", Presented at 46th Electronic Components & Technology Conference, Orlando, May 28-31 1996.

SEATON, 1996, Getting Systems Onto Printed Circuit Assemblies, Printed Circuit Design, 7/96, pp 23-29.

STRANGE, R., SUARIS, P., 1995, Meeting timing and signal quality requirements, *Printed Circuit Design*, December 1995, Vol.12, no.12.

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