Thermal Management in Embedded PC Systems

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Getting the maximum performance out of embedded PCs while keeping their size, weight and cost within reasonable limits requires careful thermal design. Under worst-case operation, excessive internal temperatures can cause embedded PCs to exceed their expected maximum operating temperature resulting initially in performance loss and, ultimately, in component failures and downtime.

Thermal management has always been important but with increasing operating frequencies for higher performance and the continued shrinking of integrated circuits (ICs) and other components, it is more than important – it's critical. Hot spots can easily be created in today's embedded PCs. According to an Intel executive at a recent technology forum, "Thermal issues are the number one problem we face today."

System designs using embedded PCs require heat dissipation from a few watts for a 386-based system to over 100 watts for a dual Pentium® 4 processor system. Compounding the thermal management task are the special environmental, high availability and longevity requirements frequently found in embedded systems. Dissipating even 10 watts can be difficult in a system that cannot use fans, must be completely sealed, and must operate in an environment where the ambient air temperature is 50°C and the maximum operating temperature is 85°C. Obtaining the proper thermal design consists of both thermal modeling and verification by actual measurements.

Thermal Layers

Thermal management in an embedded PC-based system can be modeled as a set of concentric rings. Each ring represents a thermal interface that transports heat away from the ring inside of it. Within the innermost ring is the silicon of the high performance ICs used in the system that are the primary sources of heat. The first thermal interface layer is the packaging provided by the IC vendor. The outermost ring is almost always thermally stable, ambient air but this is determined or controlled by the user. The system designer must implement application-appropriate thermal interfaces to transfer the heat of the system, starting at the ICs to this outer, stable heat reservoir of air. Table 1 shows the layers and simple description of their function.

Table 1 - Common thermal transport layers.

Layer		Description
0	IC Silicon	The source of heat
1	IC component packaging	Typically plastic
2	Heat Spreader	Diffuses the heat of several ICs across a single surface
3	Conduction	Heat flow through a thermally conductive material
4	Heat Sink	Transfers of heat to air (or another medium)
5	Convection	Moving air transports heat, may be "forced" by fan
6	Heat Reservoir	Final layer: body that can absorb heat and remain thermally stable

The number and type of layers in the thermal solution varies from system to system according to the environmental and application-specific requirements. Not all layers may be present, or allowed, in any given system. The layers might vary in order from system to system.

The packaging and features of the components, the source of system heat, represent the first layer of thermal management. Packaging material is commonly plastic for economic reasons, but in high-power ICs a metal heat slug or "flip chip" style packaging allow closer thermal coupling to the silicon die for more efficient heat transport. Many ICs, particularly processors, offer programmable power reduction features such as dynamic clock speed control. Low-power processors may be required in situations where active cooling cannot be provided and space limitations exist.

For most system designers, the use of embedded PCs starts by purchasing a board level product. Board level embedded PCs typically provide only layers 0 and 1 of the thermal solution. To implement a complete system based on this type of product, a processor heat sink and/or fan must typically be provided. In reference to the thermal model, in this case layer 2 is absent, layer 3 represents the processor to heatsink interface, and layers 4 and 5 are implemented by the heatsink and fan. So far we have only transferred the heat into the air inside the enclosure, so there must be some airflow through the enclosure or some other means to transfer the heat to the environment (layer 6).

Board-level PCs can be difficult to manage in a demanding thermal environment. The system designer may have to analyze the cooling of a number of individual heat-producing devices on the board and then provide thermal layers 2 through 6 for each of these devices as well as for the processor. Often large ICs such as Northbridge chips and video controllers will require either passive or active heatsinks. This can lead to a complex thermal solution that is closely tied to a specific board-level PC design.

Some board level products, notably "component SBC" (single board computer) or "System-On-Module" (SOM) type embedded PCs, offer a thermal interface at layer 2 in order to simplify system design. The cover plate of these modules is a heat spreader assembly that dissipates the heat of the major components across its surface, allowing conduction to be used as the next transport layer. The advantage of this approach is that the system designer need not manage the cooling of each specific heat-producing component on the module, as long as the heat spreader temperature limit is met. For thermal purposes the module can be treated as a single component.

In some "component SBC" families, the heat spreader interface is standardized for all products across a wide range of processor and performance choices. This allows the system designer to reuse a single thermal solution for successive generations of systems. Although the lowest layers of the thermal solution are specific for each PC module design, these layers become the responsibility of the SBC vendor and the system designer sees only the standardized heat spreader interface. Typically the heat spreader will be coupled to a system enclosure that serves as a heat sink. Alternatively, a conventional heatsink can be attached to the heat spreader to implement natural or forced convection cooling. An example of Kontron's ETX-P3 SBC™ with and without heat spreader is shown in Figure 1.

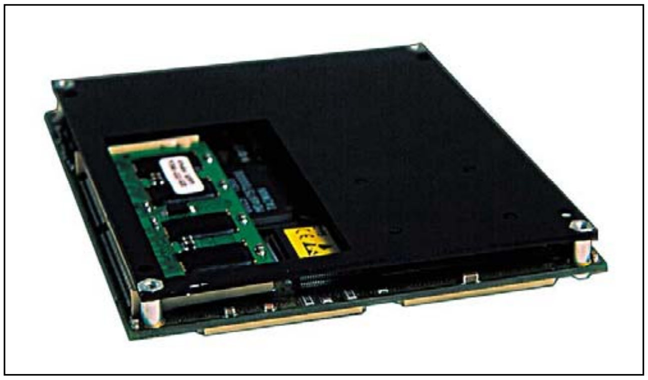

Fig 1a ETX-P3 with heat spreader

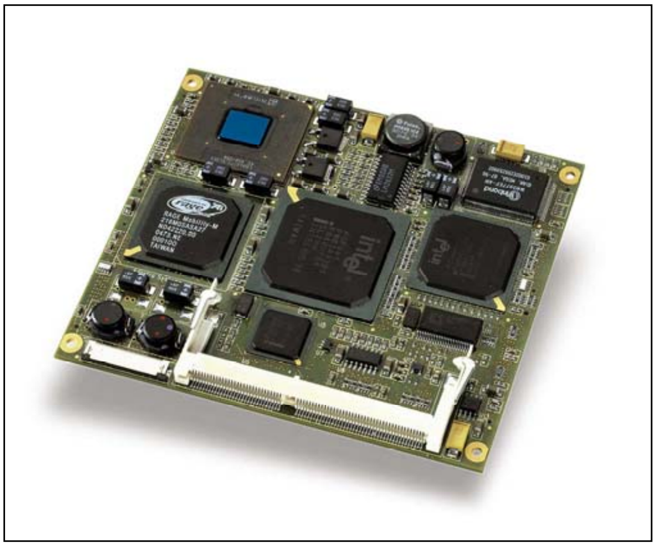

Fig 1b ETX-P3

Figure 1 – (a) The ETX-P3 SBC with heat spreader. (b) ETX-P3 SBC without heat spreader.

Thermal layer 6 of a system can be implemented in several ways. In some cases the enclosure itself can be used to transfer heat to the environment (sometimes the exterior of the enclosure is finned to facilitate this). Where airflow through the enclosure is permissible, fans or blowers are commonly used. Obtaining acceptable audible noise levels for fan cooling involves the optimum choice of fan size, blade pitch, number of blades, airflow volume and rotational speed. A smart fan controller IC and a temperature sensor can be used to control the fan according to the enclosure temperature, minimizing fan noise and power consumption. The use of smart fan control can also help extend fan mean time between failure (MTBF), which is a common concern in fan-cooled systems.

Heatpipes are sometimes used if a large amount of heat must be transferred out of a sealed enclosure. A heatpipe transfers heat by evaporating a liquid into a gas at one end and condensing the gas back to a liquid at the other. Typically a fan and heatsink are provided at the condenser end of the heatpipe, outside of the sealed enclosure, in order to transfer the heat to ambient air.

Thermal Design Philosophy

Customers have the choice to buy a board level product and do their own mechanical integration or buy a chassis/system level product. If the user puts the system together they have to deal with thermal management problems themselves. Part of the make or buy decision involves thermal knowledge, overall system cost and standard versus custom design.

An off the shelf embedded PC can address a variety of applications when the system supplier has addressed the thermal layers and specified the limits. Applying an embedded PC in an "easy" environment, such as systems for use in an air-conditioned office, is straightforward. However, a factory floor or mobile application may require operating temperatures well above 110°F (44°C). In this case, an off the shelf system is probably not going to be acceptable and a custom solution should be considered.

Enclosure Design Optimization

An example of a custom product is shown in Figure 2. In this case, Kontron worked closely with the customer and addressed the application's thermal problem with a custom solution to meet the environment requirements that the customer had determined for the application. Since the constraints were defined up front, the system designer had a number of options to deal with the thermal problem The full extent of the thermal layers could be determined and addressed at the system level design.

One of the tools used in the analysis was FLOTHERM® airflow and heat transfer analysis software to perform a computational fluid dynamic evaluation. This tool allows designers to simultaneously look at the airflow distribution and temperature distribution within the air in a 3-dimensional finite element model to avoid costly over design. Using this design tool, Kontron designers provided the initial enclosure design shape and dimensions, and the FLOTHERM software divided the unit into cells to form a computational grid. By applying boundary conditions including ambient temperature, known mass flow rates and heat sources, designers determined hot spots within the enclosure.

Using customer input for a custom embedded PC, a feasibility study was performed on a sealed enclosure with no fans using the FLOTHERM software. The enclosure was modeled as a simple aluminum box (without fins) with a wall thickness of 0.125" (3.18 mm), as shown in Figure 2a. The central processing unit (CPU) was modeled as a 533A Celeron™ FC-PGA.

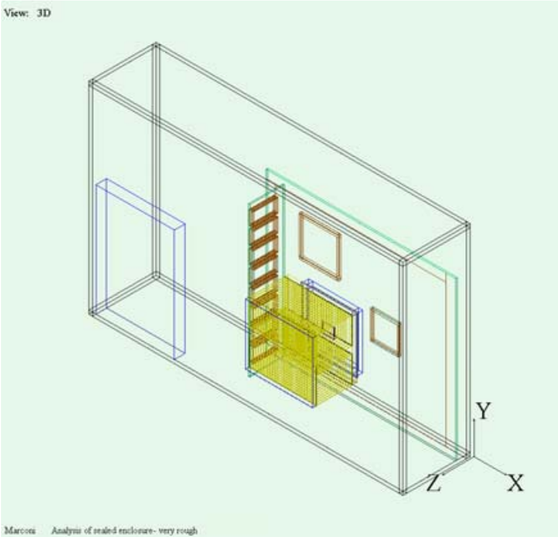

Figure 2 (a) Initial model. The enclosure was modeled as a simple aluminum box (without fins) with a wall thickness of .125” (3.18 mm). The simple heatsink design provided coupling from the CPU to the case of the chassis.

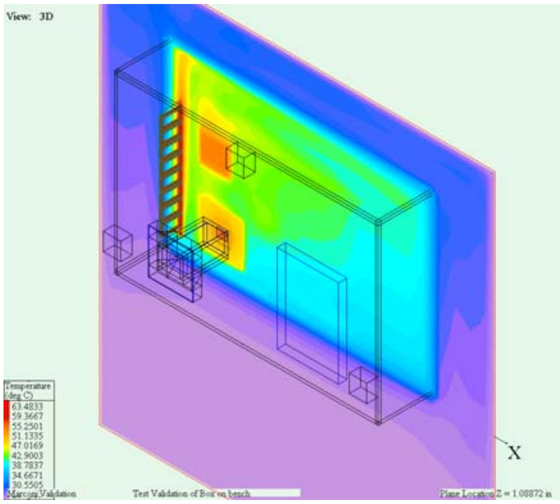

Figure 2 (b) Improved heatsink and enclosure design showing thermal profile.

Figure 2

The preliminary model utilized a heatsink that served as a coupling from the CPU die to the case of the chassis. The initial FLOTHERM analysis for the high temperature range indicated the CPU would run approximately 40°C above ambient. Other critical components including the core chipset were calculated to run at approximately 50C above ambient. This initial analysis indicated that the design would not meet the customer’s requirements.

Subsequent revisions were made to the thermal model that included:

1. Varying the wall thickness of the enclosure and the thickness of the heatsink to optimize the tradeoff between enhancing manufacturability and lowering the CPU and hard disk drive (HDD) temperatures;

2. Adding more mesh to the heatsink model to obtain a more accurate result; and
3. Increasing the contact area of the heatsink with the enclosure.

With data from the initial FLOTHERM analysis, an enclosure was fabricated and tested to validate the thermal model. Thermal test data showed the CPU to run at approximately 72°C @ 25°C ambient, while sitting on a bench oriented vertically as it would be mounted in the end application. According to the updated thermal model, the unit should have measured 53.6°C in a 25°C ambient.

A number of revisions were evaluated based on the combination of the computer-aided analysis, testing on the physical model, and the designers' previous experience and insight into thermal management issues. Key revisions included:

1. Welding the chassis sides together;
2. Increasing the surface area of the chassis;
3. Utilizing a different heatsink concept;
4. Perforating the back of the enclosure for improved airflow; and
5. Evaluating the addition of a 1000 cubic feet per minute fan.

Table 2 shows the temperature rise above ambient that occurred for three final configurations. The chosen enclosure produced the temperature results shown in Figure 2b. The final selection was made based on manufacturability as well as meeting the end customer's performance requirements.

Configuration	HDD Temp (above ambient)	CPU Temp (above ambient)
No blower, natural convection/conduction chassis with fins & HDD mounted externally	7-9°C	43°C → 33°C possible
Blower, sheet metal chassis with louvers & HDD mounted internally	15°C	25°C
Blower, sheet metal chassis with louvers with the HDD mounted externally & conducted to the phone unit	10°C	25°C

Table 2 – Measured temperatures for three configurations.

Conclusions: Avoiding Thermal Problems

The internal temperature rises that can occur in today's embedded PCs must be addressed early in the system design. A thermal management model has been discussed that uses thermal layers from the heat sources to the heat reservoir. Understanding the thermal design issues can help a system designer choose among board level, module, and chassis system products available in the marketplace.

For special environments a custom solution may be required and a specification of the environment will be necessary for system design. Using simulation tools and thermal measurements on preliminary hardware, custom thermal solutions can be evaluated early in the design process for performance and cost effectiveness, eliminating expensive field testing or retrofitting.