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A Heat Management Primer

Thermal design problems can lead to unpleasant results. Testing your system and using thermal simulation software early in the process can help eliminate problems before it's too late. This article provides some basic rules about thermal management to help you determine whether or not your design is thermally correct.

Welcome back to The Darker Side. Chip designers do incredible things. I just read that the latest Intel Itanium baby, code-named Poulson, integrates no less than 3.1 billion transistors. That's probably reasonable, as it includes eight 64-bit cores and 54 MB of cache memory on chip. Well, Intel also proudly announced that this chip is less power-hungry than its predecessors, requiring "only 170 W." To me, this emphasizes that Intel's thermal engineers are at least as clever as their silicon engineers! Let's make a comparison: Your electric home heater is roughly 60 x 60 cm, whereas the chip die is made of maybe one square cm of silicon. If your heater had the same power density as this Itanium chip it would dissipate no less than 60 x 60 x 170 W, which is 612 kW!

Even if your designs are far from these extreme power densities, it is not unusual to have some watts to dissipate on a PCB. Motor drivers, RF, or audio amplifiers come to mind, but high-power dissipation is also usual on high-speed digital boards. For example, my company's last FPGA project eats up close to 10 A on the 1.8-V power rail.

This month I will devote my column to thermal design, a topic that Ed Nisley recently covered in his April 2011 article ("Thermal Performance," Circuit Cellar, 249). Let's be honest: I'm not a specialist in thermal problems, but I did have some unpleasant surprises while working on a couple of designs (which meant that some chips exploded with heavy smoke). Niels Bohr once said that an expert is a person who has made all the mistakes that can be made in a very narrow field. I'm far from a thermal expert, but I will try to limit your personal exposure by providing you with some basic rules.

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**Figure 1**—Thermal engineering is all about thermal transfers. If you put an electronic board inside a hypothetical perfectly thermally insulated enclosure, its temperature will rise up to a meltdown with a rate proportional to the dissipated power and inversely proportional to the heat capacity of the system.
ENERGY DISPERSAL

Let's start with the basics: Thermal management is all about energy dissipation. This is, in fact, a direct consequence of the first law of thermodynamics, which states that energy can't be destroyed (or created). Imagine that you have an electronic board that is continuously dissipating a small power \( P_{\text{thermal}} \) equal to 1 W. Assume for the moment that you have a perfectly insulated enclosure. Put the board inside this enclosure and switch the power on. What will happen?

As there is no thermal exchange between the inside of the enclosure and the rest of the universe, the board temperature will linearly increase over time (see Figure 1). Every second there will be an energy \( E_{\text{thermal}} = P_{\text{thermal}} \times \text{time} = 1 \text{ W} \times 1 \text{ s} = 1 \text{ J} \) dissipated inside the enclosure by your electronic board. This energy can't go anywhere, so every second the board temperature will increase by \( \Delta T = \frac{E_{\text{thermal}}}{C_h} = \frac{1}{C_h} \), degree. In this formula, \( C_h \) is a constant called the heat capacity of the board. If the board is homogeneous, say made of a full sheet of copper, then its heat capacity will simply be proportional to the mass of the board. More specifically, it will be equal to the mass of the board multiplied by the so-called specific heat of the copper. You will find this value in any physics book; for copper it is 0.385 J per gram per \( ^\circ \text{C} \). To be exact, we should also add the heat capacity of the air around the board, but it is small enough to neglect.

So, the math is straightforward. For example, imagine that you fix a heavy 1 kg copper heatsink to the 170-W Titanium processor I mentioned before and put the assembly in a perfectly thermal-insulated enclosure (which would be a bad idea). Every minute the assembly temperature will increase by 26.5\(^\circ\text{C}\) [i.e., \((170 \text{ W} \times 60 \text{ s}) / (1,000 \text{ g} \times 0.385 \text{ J/g} \cdot ^\circ\text{C})\)]. After 15 minutes the processor and heatsink will exceed 400\(^\circ\text{C}\), and your expensive processor will definitively melt down.

THERMAL TRANSFERS

Fortunately, perfectly insulated enclosures don’t exist. With any actual packaging a part of the energy dissipated inside will find its way to the outside, more or less efficiently depending on the design. This thermal transfer will limit the temperature rise of the electronics up to an equilibrium state, where the thermal losses of the environment are equal to the energy dissipated by the electronic components.

How is thermal energy dissipated to the outside world? There are three kinds of heat transfers (see Figure 2). The first, and usually the most efficient one, is conduction. Joseph Fourier (the inventor of the Fourier transform) stated in 1822 that the thermal flux between two closely spaced points is proportional to the temperature gradient and opposite in sign. Let’s illustrate that with the example of a thin sheet of homogenous material (see Figure 3). Fourier’s law then says that the heat transfer [in W] between the two sides of the sheet will be proportional to the temperature difference of the two sides, proportional to the area A of the sheet [the larger the better], inversely proportional to its thickness \( t \), and flowing from hot to cold sides. The multiplicative coefficient is called the thermal conductivity of the material. Its value is, for example, 383 W/m.K for the copper which is one of the best thermal conductors. The formula is the following:

\[
Q_{\text{w}} \text{ (W) = } k \times (T_2 - T_1) \times \frac{A}{t}
\]

This seems reasonable, doesn't it? Let's go back to electronics. Imagine that you have a power transistor on a very large heatsink, assuming for the moment to stay at a constant 25\(^\circ\text{C}\). What will the temperature of the transistor die be if the transistor dissipates a given power \( P_{\text{thermal}} \)? When you switch on the system the transistor is obviously at 25\(^\circ\text{C}\), too. It will then rise, depending on its own heat capacity, then thermal energy will flow to the heatsink. At a given time, an equilibrium will be reached, which means that the heat transfer between the transistor and the heatsink is exactly equal to the power \( P \) dissipated by the transistor. In a nutshell, the respective heat capacities of the parts define the dynamic thermal behavior of the design, but their respective heat transfers define the final temperatures. Then what is the static temperature difference between the transistor die and the heatsink? Assume

Figure 3—An example of conduction heat transfers illustrated by a thin sheet of material. The heat transfer (in watts) between the two sides of the sheet is proportional to the temperature difference of the two sides, to the area \( A \) of the sheet, inversely proportional to its thickness \( t \). It is flowing from hot to cold sides. The overall multiplicative coefficient is called the heat resistance.
that the transistor package is a sheath of metal and just invert the prior formula:

\[ P_{\text{thermal}} \times \left( \frac{s}{(k \times A)} \right) = P_{\text{thermal}} \times R_{\text{thermal}} \]

Therefore, this temperature difference at equilibrium is simply proportional to the power to be dissipated: if it is 20°C for 1 W, then it will be 100°C for 5 W. In fact, components manufacturers directly give the multiplying coefficient, called the thermal resistance, in an easy to use “°C/W” unit. For example, look at the extract of an NXP BUJD203AX high-voltage transistor (see Photo 1). With such a datasheet, you now that the typical junction to ambient thermal resistance when the transistor is in free air is 55°C/W. Therefore, if the transistor dissipates 2 W then its die temperature will be 110°C (i.e., 2 \times 55) above ambient temperature.

This is conduction. The two other ways of heat transfer are convection and radiation. Convection is the process of heat transfer to a moving fluid, which is usually air, or it may be water in your car engine, or another exotic fluid in your last PC’s thermal pipe system. Let’s restrict it to air. When airflow passes around an object it takes part of the object’s heat. There are two convection modes: the easiest is forced convection, where the airflow is set by a fan or something similar. In this situation, the heat transfer through convection is roughly proportional to the temperature difference between the object and the cooling fluid, and proportional to the airflow. Forced convection is similar to conduction. The natural convection, where the airflow is generated by the temperature difference itself, is more complex as the relationship between temperature difference and the heat transfer is no longer linear. The principle is, however, the same. Interested readers could have a look at A Heat Transfer Textbook, by John H. Lienhard and son, available or MIT’s server. Roughly natural convection is close to conduction when the temperature difference between the heatsink and the ambient air is high, above 75°C, but is significantly less efficient when it is lower, as the airflow is very low. I will give you an example later.

To be complete, heat radiation is the process of heat transfer through electromagnetic radiation, meaning through the natural infrared radiation of any object hotter than –273°C. However, radiation is usually low compared to conduction and convection, except at extremely high temperatures. I will assume it could be neglected in your design.

HEATSINKS

Let’s move on to a classic application. You have an electronic component that has to dissipate a given power and you must find an adequate heat dissipation solution. Suppose you are building a high-voltage linear power supply based on the BUJD203AX transistor I used in the prior example [see Photo 1]. Assume that the input voltage is 110-V DC, that the output voltage could be set between 1 V and 100 V, and that the maximum output current is 100 mA. Lastly, the product will only be used in a lab with an ambient temperature of up to 35°C in the summer. Do you need a heatsink, and if so, which one? First, you have to calculate the worst case power dissipation of the transistor. For a linear power supply, the worst case is achieved when the output voltage is minimal, here 1 V, and of course when the output current is maximal. Here the corresponding power dissipation will be 10.9 W (i.e., \((110 \text{ V} - 1 \text{ V}) \times 100 \text{ mA}\)). If you had the silly idea not to use a heatsink, then the temperature difference between
the transistor die and the ambient temperature would be, based on the $R_{Th}$ (junction to ambient) value given by the supplier. 600°C [i.e., 10.9 W x 55 °C/W]. Smoke around the bench for sure.

To calculate the required heatsink you have to take the opposite approach: From the transistor datasheet you know that the absolute maximum junction temperature is 150°C. It is safe to not get too close to this limit, so let’s take a maximum of 35°C. If the heatsink is installed outside the enclosure it will dissipate through natural convection and the ambient air around the heatsink will be at the maximum 35°C. Be careful, as a significantly higher ambient temperature would need to be calculated (or measured) if the heatsink was installed inside the product, as the “ambient” temperature would then be the maximum temperature inside the enclosure, which then depends on the enclosure inside to outside thermal resistance.

In our example, the worst-case temperature difference between the transistor die and the ambient is then 100°C [i.e., 135°C – 35°C]. As the power to be dissipated is 10.9 W, then the maximum allowed thermal resistance between the die and the ambient air is 9.18°C/W [i.e., 100°C/10.9 W]. However, the datasheet states that the thermal resistance between the transistor die and the heatsink, with thermal compound, is already 4.8°C/W. Hopefully, this transistor is in a fully plastic TO-220 package so you won’t need to add an insulator sheet, which would add another small thermal resistance. Therefore, you need to find a TO-220-compatible heatsink with a thermal resistance lower than 4.38°C/W [i.e., 9.18 – 4.8].

Are your problems over? No, for two reasons. First, let’s calculate the maximum heatsink temperature: it will be 82.7°C [i.e., 35°C + 4.38°C/W x 10.9 W]. This temperature is probably above a safe limit for a user-accessible part. If you want to keep it, say, under 65°C, then the maximum heatsink resistance becomes 2.75°C/W [i.e., $(65°C – 35°C)/10.9 W$]. Second, as the heatsink is used in natural convection mode, you must include a derating factor if the temperature difference between the heatsink and the ambient air is not higher than 75°C, as the air flow will be very low. You can find the required temperature correction table on Aavid Thermalloy’s website (see references). For a 30°C difference between air and heatsink temperature the derating factor is 1.25, so you will need to find a heatsink with a thermal resistance below 2.2°C/W [i.e., 2.75/1.25].

That’s already a large baby. For example, the Aavid Thermalloy OS518-100B heatsink (Photo 2) will just fit the bill: 2.2°C/W. It is 54 x 38 x 100 mm. But to be safe, I would use a slightly larger one.

If you are space restricted, one way to use a smaller heatsink is to use forced convection. This means putting the heatsink inside an enclosure and adding a fan and whatever else is needed to force the fan airflow through the heatsink and out of the box. You will also find the corresponding performance factor table on Aavid’s website; the improvements are impressive even with a very small fan. Take care that the heatsinks optimized for forced air convection are different than the ones optimized for natural convection: their fins are more closely spaced. Look at the heatsink on any high-end PC video card, for example. Lastly, if you need to build a heatsink yourself, you will have to measure its actual thermal resistance, which is not hard to do, or calculate it. The calculation is not difficult for forced air heatsinks; there are even free calculators on the web [see Photo 3]. In the case of natural convection this may be more tricky.... Let me know if you find good references or tools adequate for this purpose.

**ELECTRICAL MODEL**

I assume that you are more fluent with electrical schematics than with thermal problems, right? Then you will be pleased to know that there is an easy way to model a thermal system through its electrical equivalent. Remember that in the case of conduction, the temperature difference is the product of the thermal resistance and the thermal power transfer. Remember Ohm’s law, $V = IR$! If we map a temperature to a voltage, a thermal resistance to an electrical resistance, and a thermal power transfer to a current we have a very good analogy!

Moreover, let’s recall the first example I gave you about a system in an insulated enclosure. Its temperature was rising infinitely with a rate proportional to the heat capacity of the system. And, of course, you have already guessed that the corresponding electrical model of heat capacity is simply a capacitor. Do you remember the relationship between

**Photo 5**—Novel Concepts provides interesting thermal calculators on their website, such as this forced-air heatsink calculator.
the charge of a capacitor and the voltage across its terminals? It is simply $Q = C \times V$. Furthermore, the heat energy stored in a system is its heat capacity (similar to $C$) multiplied by its temperature increase (similar to the voltage $V$).

In summary, you can easily model a thermal system through voltage sources, resistors, and capacitors. You can then use any electrical simulation software, such as Simulation Program with Integrated Circuit Emphasis (SPICE), to get a simulation of the thermal behavior of the system. Let's try it using the example of the high-voltage power supply discussed earlier in order to find out the evolution of the transistor die and heatsink temperature over time. We already know the power dissipated by the transistor ($10.9$ W), as well as the die to heatsink resistance ($4.8$ °C/W), and the heatsink to ambient air resistance ($2.2$ °C/W). We are missing the heat capacitance of the transistor and heatsink. This specific heatsink weighs $164$ g, so its specific heat is $164$ g times the specific heat of aluminum which is $902$ J/g°C, resulting in $148$ J/°C. Similarly, we can guess that the heat capacitance of the transistor will be very low as it is mainly plastic, say $0.5$ J/°C. We then have everything needed to simulate the system, as illustrated in Figure 4. The heatsink temperature rises as expected up to $60°C$, with $58°C$ reached in about $1000$ s, or 15 minutes. The die temperature quickly rises up to $88°C$ then follows the heatsink temperature increase up to a safe $112°C$. I have done this simulation using Labcenter's Proteus, but you can, of course, use any SPICE-based tool.

**Simulation Tools**

I'm sure that from time to time you have power dissipating components on a PCB, without any external heatsink. For example, if you build a small DC/DC converter then the switching chip or transistor may have to dissipate some hundreds of milliwatts and will usually be an SMT chip. Hundreds of milliwatts may not be much, but you will need to get this heat out. Usually the best solution is to design a PCB with as many copper planes as possible, as copper conductivity is several orders of magnitude better than epoxy! Four layers of PCBs help dramatically, as a full layer could be dedicated to the ground plane. You must also optimize the thermal transfer between the dissipating components and the copper planes. This means adding plenty of vias everywhere, and in particular, behind the key components. If the external enclosure is metallic, then of course you must provide a good heat transfer between the PCB and the enclosure through large surfaces of contact and good screws. You can also use thermal transfer pads, which are low-thermal resistance foams. Gluing one of them on top of a problematic FPGA and pressing the assembly against the side of a metallic enclosure has solved a lot of designers' dilemmas as it enables a direct thermal path.

**Figure 4:** A thermal system can be modeled by its equivalent electrical model. Temperatures map to voltages, heat power transfers to currents, thermal resistances to electrical resistances, and thermal capacitances to capacitors. Here the unknown value is the die temperature, but the power to be dissipated is fixed and modeled through a current source under Proteus.
How do you know if the design is thermally correct? The first solution is to build it...and to test it. Switch on the board in the worst operating condition and measure the temperature of all critical components. This can be done manually with a low-cost hand-held infrared thermometer, but your life will be much easier if you are lucky enough to get access to a thermal imager (see Photo 4).

The other solution is to use thermal simulation software as easily as possible in the development cycle. There are several good high-end packages on the market, such as Mentor Graphics’s FloTHERM, but these tools are usually, well, far from cheap, and as far as I know, they need a significant level of expertise to be efficiently used. Fortunately, there are now at least two free solutions: the first one is WebTherm. This tool is offered by National Semiconductor as part of their web-based WebBench DC/DC converter design tool suite which is based on FloTHERM. It enables you to quickly evaluate the thermal performances of powers supplies developed under the WebBench.

The other solution, which I find interesting, is Vishay’s ThermaSim. I love this one: it just enables you to select a couple of semiconductors (from Vishay’s catalog, of course), place them wherever you want on a PCB, indicate how much power will be dissipated by each component, select the characteristics of the PCB (size, number of layers, copper spreading, etc.), click on a button, and a couple of minutes later you receive a pretty thermal simulation via e-mail (see Figure 5)! It’s impressively flexible and simple to use. Give it a try.

PREVENTING DISASTER

Here we are. I know that thermal problems are a significant pain for a lot of electronic designers. Often the issue is discovered too late, and this can lead to burdensome development delays and high re-engineering costs, as everything, including the mechanical design or even the product’s concept, may need to be reworked. I hope that this introductory article will help you head off the problem before it is too late. Once again, I’m not a thermal expert, but I’ve suffered more than once. Perhaps my advice will help you to save some MOSFETs from heat destruction.

Robert Lacoste lives near Paris, France. He has 20 years of experience working on embedded systems, analog designs, and wireless telecommunications. He has won prizes in more than 15 international design contests. In 2003, Robert started a consulting company, ALCOM, to share his passion for innovative mixed-signal designs. You can reach him at lacoste@alcom.com. Don’t forget to write “Darker Side” in the subject line to bypass his spam filters.

RESOURCES


—, “Forced Air Correction Factors,” www.aavidthermalloy.com/technical/convect_table.shtml


SOURCES

OS518-100B Heatsink
Aavid Thermalloy | www.aavidthermalloy.com

Proteus CAD Tool suite and analog simulator
Labcenter Electronics | www.labcenter.co.uk

FloTHERM Simulation suite
Mentor Graphics | www.mentor.com

WebTHERM Online thermal simulator and WebBench
DC/DC converter tool suite
National Semiconductors | www.national.com

Online forced convection heatsink calculator
Novel Concepts, Inc. | www.novelconceptsinc.com

BUJD203A High-voltage transistor
NXP Semiconductor | www.nxp.com

WinTherm Simulation suite
ThermoAnalytics, Inc. | www.thermoanalytics.com

ThermaSim Online thermal simulator
Vishay Intertechnology, Inc. | www.vishay.com
Across

2. Used in lieu of text, e-mail, IM, etc.
6. Gives instructions to operate
7. Uses reasoning
10. Plan
11. 1:2
13. Most basic form of communication
14. A device cats are especially fond of
15. A designated location
16. The distance between two points
17. May denote exclusivity
18. Speaks the language of programmable devices
20. An energy value

Down

1. Search
3. Woven by a very large spider [three words]
4. S/H [three words]
5. Allows for sharing, if you’re in the loop
8. A communication process that converts information into symbols
9. Provides performance details
12. Storage
19. Minimum of two

The answers will be available in the next issue and at www.circuitcellar.com/crossword.