Thermal Load Boards – Another Thermal Management Design Tool

By
Bernie Siegal
Thermal Engineering Associates, Inc.
612 National Ave
Mountain View, CA 94043-222
650-961-5900
bsiegal@thermengr.com

Abstract

This paper describes a tool that can be used in the thermal management design of electronic printed circuit assemblies at both the board level and the system level. The thermal load board tool simulates actual thermal conditions that can be easily modeled and validated. The approach described herein is useful in minimizing electronic system development time and cost.

Keywords

Thermal Load Board (TLB), thermal management design, thermal simulation, simulation validation, heat spreader, package simulation, printed circuit assembly (PCA), bare die simulation

Nomenclature

Thermal Load Board – TLB
Printed Wiring Assembly – PCA
Printed Circuit Board - PCB

1. Introduction

A common problem in the design and development of complex heat-producing electronic assemblies and systems is how to anticipate thermal management issues before all the components, especially state-of-the-art and/or custom integrated circuits, are available and the final electrical and mechanical design are completed. Thermal simulation models provide one insight into the thermal issues but assembly and system designers also need an empirical view of the thermal issues. Thus, the thermal management solution designer needs another tool to help increase the confidence in the thermal design.

That tool is the Thermal Load Board (TLB). The TLB is used to simulate an application printed circuit assembly (PCA) either before all the heat-producing components are available for mounting on the application PCA or if the heat-producing components require complex electronic circuitry to create heat within the components. The board is typically designed to be as mechanically and thermally equivalent to the application PCA as reasonably possible, and usually offers a way to vary the power dissipation of the elements that simulate the heat-producing components. The latter capability is necessary for validating a simulation model over some heat generation dynamic range in terms of power dissipation levels and time-variant heating and to respond to changes in the environmental conditions.

2. Definition

The TLB is usually a "form and fit" replacement for the application PCA. The board is designed to have the same X and Y dimensions and shape with the same mounting holes and key component attachment holes as the application PCA. In some applications, such as for a motherboard in a notebook computer, the TLB must have multiple cutouts and extensions in order to match the packing requirements with many other non-motherboard-mounted components, such as hard drives, batteries, optical drives, etc. In other applications, such as blade server motherboards, the TLB is more rectangular with relatively few cutouts but with many component mounting holes and usually provisions for one or more daughter-boards for memory or communications functions. In some cases, cutouts and mounting arrangements must be included for fiber optic transceivers as well.

Dimensions in the Z direction are often critical for several reasons. The height of components on the TLB must be considered for simulating airflow considerations – blockages, restrictions, etc. – in order to generate a true representation of the thermal environment. There must no mechanical interference with other components and assemblies within the system. The TLB is of no value if it can not be inserted in a real system. Finally, and perhaps key in the thermal management design, the height of all heat sources that must mate with thermal solutions – i.e., heat sinks, heat spreaders, etc. – must precisely match the dimensional requirements to insure an acceptable mating of the two.

The TLB can be very complex, with every single heat producing element on the application PCA faithfully simulated, or very simple, with only key heat producing components simulated. The former is usually costly to implement, requires more time to design, and is more difficult to setup and use. The latter overcomes these obstacles but, if too simplified, it may not accurately simulate the application PCA.

3. Design

There are several approaches that can be use to create the TLB heat producing elements for simulating the PCA's actual electronic components. The simplest approach is to use resistors but there are some issues to be considered with this approach. The key issues in designing a simulation replacement for an actual component are:

1. The X-Y dimensions
2. The Z dimension
3. The component heat generation
4. Heat transfer into the printed circuit board
5. Heat transfer into the potential thermal management solution
6. Heat simulation dynamic range

The first two of these are simple and obvious, but become complex when combined with the third issue. Generating 2W or more for a 7mm X 7mm X 0.8mm component becomes a little tricky, especially when some reasonable heat simulation dynamic range is required. If only 1W heat generation and +50% dynamic range is required then a 2X4 array of 1206 surface mount chip resistors would meet the requirements of 1), 2), 3) and 6). However, going beyond 1.5W will increase the dissipation level beyond the chip resistor specifications. If the actual component normally transfers some or all of its generated heat into the printed circuit board, then the chip resistors mounted directly on the board satisfies 4) easily. However, if most of the generated heat is supposed to be transferred into a heat sink or heat spreader (i.e., 5) above), then the chip resistors should not be mounted directly onto the board, which requires a different mounting solution.

Alternative heat generation approaches include:

a) Metal foil heaters – useful alternatives but are more difficult to implement. The available X-Y dimensions are limited and the Z dimensions are usually very small. The latter typically requires additional cost in adding bulk to the heater, especially if the total simulation must have a precise height to satisfy 6) above. Power density issues and purchase availability may also be an issue for specific resistance values and size.
b) Rectifier diodes – either PN or Schottky junction type in a surface mount package are a good alternative in situations when the chip resistor power dissipation specifications are not sufficient to meet the heat generation requirements. Several surface mount diode packages can typically dissipate about twice the power dissipation of comparable-size chip resistors and are readily available. Diodes, however, are best driven by a current source, rather than the more readily available voltage source that are used with the resistors. The heat transfer and dynamic range issues are similar to those for the chip resistors.
c) MOSFET and Bipolar Transistors – these devices can generate relatively large amounts heat in a small package and can be attached to a copper pad on the board to satisfy 4) above. To satisfy 5) above, however, the package typically has to be mounted upside-down in someway to achieve the desired interface height for the heat sink surface. The electrical circuitry for driving these 3-terminal devices is much more complex than that required for the other approaches.
d) TTVs (Thermal Test Vehicles) – usually supplied by chip manufacturers but now available from third parties[i,ii], these devices are thermal test chips (TTCs) mounted in packages to physically match the actual semiconductor component as possible, especially in the exposed die (i.e., die backside accessible for direct heat sinking) package configuration. TTCs typically contain heating resistors and diode or resistive temperature sensors, and the chip size closely resembles the actual chip. The biggest problem with TTVs is that they do not always exist – developing a TTV for a specific chip is expensive and time consuming – and, even when they do exist, are usually difficult to get. The advent of third party suppliers has mitigated this problem to some extent but, even with arrayable TTCs it may not be possible to get the exact size (X, Y & Z) and power dissipation/temperature sensor configuration to exactly match the actual component.

Sometimes it is desirable to put a heat spreader over the top of the heating element array to either simulate a uniform

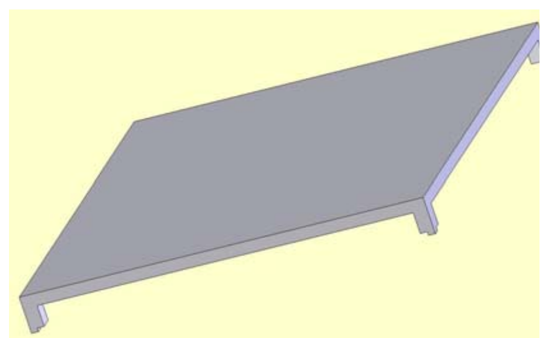

Figure 1 Heat Spreader Table

heat source area or to allow some significant heat transfer into the thermal management solution. This can typically be done with a metal plate of copper or aluminum. The thickness of the plate is determined by the simulation requirements and the thickness of the simulated heat source.

Maximizing the heat transfer into the thermal management solution, to satisfy 5) above, requires some

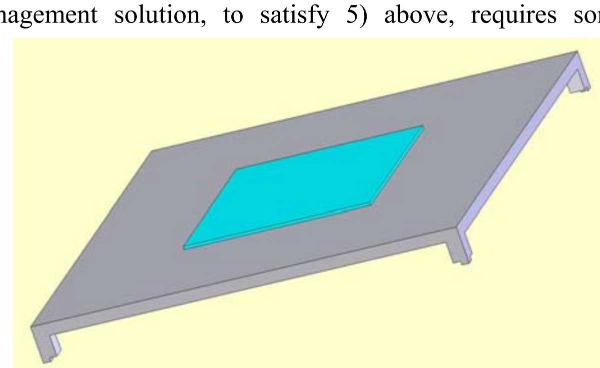

Figure 2 Heat Spreader Table with Bare Die simulation

creative design. The best way to limit heat flow into the board is to provide an air gap between the heat producing elements and the board. However, it is also important to set the maximum height to properly mate with the heat sink or heat spreader. When attempting to simulate a thin component, this can be quite challenging. One approach for accomplishing this is to use a metal table structure as shown in Figure 1. The table core thickness is equal to the difference between the desired component height and the sum of the heat dissipater thickness, the sub-mounting thickness and the desired air gap. This sum is also height of the table legs. If this configuration is use to simulate a bare die package, then the table core is reduced slightly to provide a top plateau matching the die size, as shown in Figure 2.

The design of the TLB must also take into account the thermal properties of the PCA. Most system-level PCAs use multilayer boards with anywhere from two to 16 (or more) internal copper planes. Depending on the area coverage of each layer, this will make the board very thermally conductive. Failure to take the board thermal properties into account will lead to simulation boards and models that do not match the actual PCA thermal performance. However, including all the copper layers into the TLB design will significantly increase the TLB cost. Alternatively, the TLB internal layers can be reduced to two, sometimes four, by making each layer thicker so that one TLB layer simulates the copper content of several PCA board layers.

The next design issue deals with how electrical connection is made to the TLB. The electrical connections to the TLB will vary for a number of reasons. If there are high (>3A) currents required, then either large wires or multiple small wires will be required. If very accurate knowledge of the power dissipation in all or specific heating arrays is required, then the use of Kelvin Connections (i.e., 4-wire with separate force and sense lines) should be used. Also to be considered is how fine grain is the need for heating power control. For example, if there are four exactly the same memory chips being simulated, they can be powered in parallel with a single supply or powered separately each with a different power supply. The former alternative may be good enough if the memory chips are in close physical proximity to each other but not good enough if they are dispersed across the TLB or mounted each side of the board. The latter alternative is useful if one or more of the memory chips are likely to run hotter than the others under specific software loading conditions. In most situations, the TLB should be designed to allow for either alternative.

In most applications, it is most desirable to make electrical connections outside of the TLB enclosure. This avoids issues with the electrical connectors blocking some air flow or affecting the board thermal performance, which potentially influence the thermal simulation results. There three approaches for making electrical connection to the TLB. These are:

a) Flying leads – wires of some suitable length (typically in the range of 1 meter or more) are soldered at one end directly to the board. This is the easiest approach if the number of wires is relatively small and if the TLB will not be moved once put into place. An enclosure cutout may be required if the wires can not be routed through existing enclosure holes.
b) Connector(s) – one or more connectors (typically some form of boxed header type) mounted directly to the board. This approach is useful if the board will often be removed and remounted in its case. However, if the connector(s) are fairly large, a suitable enclosure cutout is required to allow the connector(s) to slip through. Then this cutout must be appropriately treated to provide air flow conditions as close to actual PCA conditions as possible.

Edge Finger Connector – the electrical connection extension is designed with metal connection fingers on the side farthest from the TLB body. This approach requires the

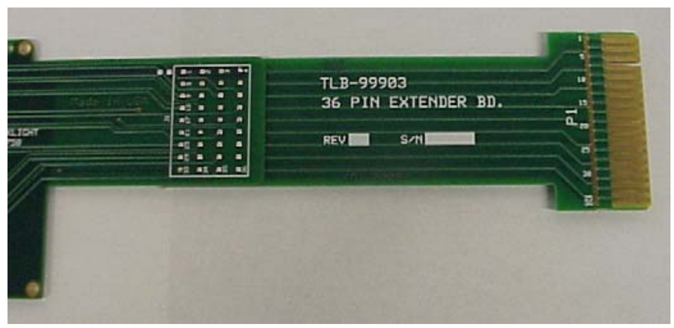

Figure 3 Edge Finger Extender Board

smallest enclosure cutout and is relatively easy to design. The number of connections can exceed 80 in a relatively small physical space, providing a large amount of connection flexibility, such as the option for the multiple memory chip configuration discussed previously. Multiple fingers can easily be paralleled to handle high currents. On the negative side, it is imperative that the board thickness lie within the mating edge finger connector acceptance range. If the board is too thick, it won't fit into the connector. If too thin, a good solid electrical connection can not be assured. Most printed circuit board fabricators do not like dealing with boards having multiple thicknesses and those fabricators that will tackle the job charge significantly more for the boards. The alternative is to design and fabricate a small second board of the correct connector-mating thickness that can be easily attached to the TLB's electrical connection extension. An example of this approach is shown in Figure 3. Solder eyelet feedthrough jumpers connect the two boards together.

4. Measurement Considerations

The one major measurement issue in the use of the TLB is centered on determining that actual power dissipation of each of the heat generating elements. Most of the elements will not require precise ($\leq$1%) knowledge of the power dissipation. But those that do, such as the CPU, GPU and specialty chips, require a very accurate measurement of voltage across the element and the current through the element. Using Kelvin Connection, as mentioned above, right at the physical location of the element, eliminates voltage drops along the connection traces so that the desired accuracy can be obtained.

Although most TTVs contain temperature sensors, it is usually best to have temperature measurement capability at other locations on the TLB. Thermocouples can be used but mounting them in a non-intrusive manner can sometimes be difficult. The thermocouple leads have to be brought out separately, as running the connection through connectors can cause measurement issues. An alternative is to mount either chip thermistors or small-package temperature sensing diodes on the board; their electrical connections can be easily routed through the TLB connector, These devices require calibration before use to obtain accurate temperature values. The temperature sensors should be placed in locations that would best suit thermal simulation validation. For example, putting a temperature sensor on the opposite side of the board in center of the CPU location provides a way to confirm that the CPU TTV junction and board temperatures are tracking correctly. Usually only two or three board-mounted temperature sensors are sufficient but number can easily go to ten sensors or more on very complex TLBs.

One measurement area not normally addressed on TLBs is that of air flow. In some TLB applications, such as for blade server simulation, the knowledge of air flow velocity and direction in certain critical locations would be very helpful in further validating thermal simulation models. While there are some air flow sensors exist that could be implemented on TLBs, they currently require separate connection and instrumentation for operation. This situation will change as new sensors are developed and brought to market in the near future[iii].

5. Design Examples

A typical TLB simulator for a dual CPU blade server board is shown in Figure 4 without the CPU sockets and mechanical apparatus for mounting a thermal solution. The large grey block on the lower right corner is the connector used on the PCA; it provides a mechanical interface to the blade server card cage and mimics air flow restrictions but is not used for electrical connections to the TLB. The DIMM sockets are wired to accept DIMM thermal simulators. The CPU simulators are TTVs with both heaters and temperature sensors. All the TLB electrical connections are made via the sockets mounted the three extensions on the left; these extensions pass through slots on the blade server front panel. The two heating resistor arrays along the bottom edge simulate power supply components while the array in top right quadrant simulates a large ASIC glue logic chip. There are three board-mounted temperature sensors – one mounted on the top board surface between each CPU and memory sockets and one mounted under the ASIC chip on the back

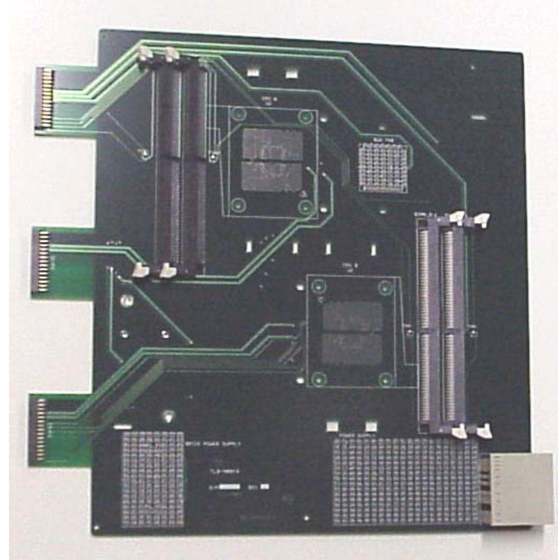

Figure 4 Blade Server TLB Simulator

side of the board. This board also has several mounting holes and solder eyelets for two different types of daughter boards.

Figure 5 shows an example of how to increase the board thickens to insure proper mating with an edge finger connector. The thickness of the small board on the left, combined with that of the TLB on the right, is designed to match the edge finger connector's acceptance thickness. The small board is turned over, positioned correctly at the edge of the TLB, and then connected to the TLB with small wire jumpers through mating solder eyelets on both boards. The mating edge finger connector can also be mounted on a small pcb that has labeled solder eyelets for flying lead connections to appropriate power supplies and measurement instruments.

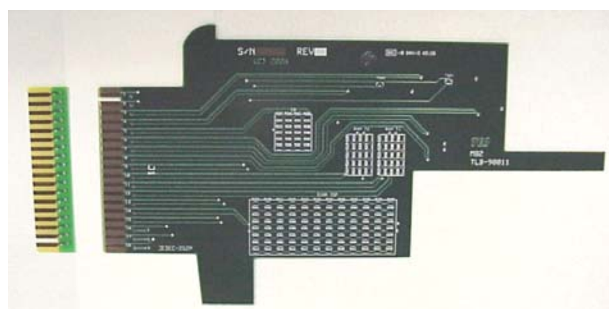

Figure 5 TLB add-on board to increase thickness

This arrangement requires only a very small slot to be created in the enclosure side wall to insert the TLB into position.

The TLB shown in Figure 6 was designed to simulate a high performance desktop computer motherboard. The light green board area below the horizontal row of four holes is the electrical connection extension area. The 15 hole pads (3 on left, 3 on right, and 9 in the center) are threaded screw terminals for connection of high amperage wiring for powering up the dual CPU TTVs and the logic controller chip TTV. Boxed header connectors go in the white rectangular box areas; these provide electrical power and measurement connection for the lower current resistive heaters on the board and in the dual four-unit memory modules associated with the CPUs. The back of the TLB has several board-mounted diodes in SOT packages for temperature sensing in key locations around the CPU locations. The white rectangular regions are chip resistor arrays that simulate power supply and interface logic areas.

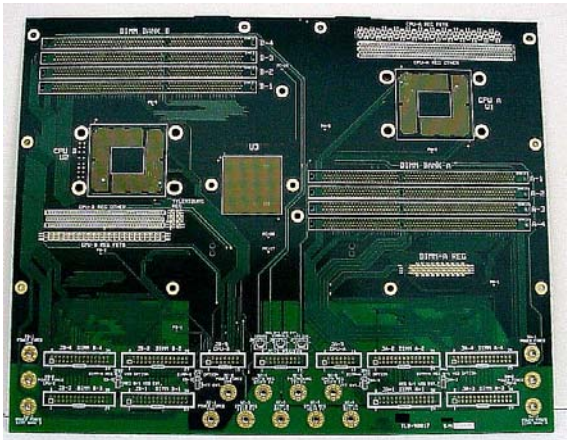

Figure 6 Desktop Computer Motherboard TLB

Figure 7 shows two views of a TLB for notebook computer simulation – one view of the basic board and a second view of the same board with heat spreader plates over some heating

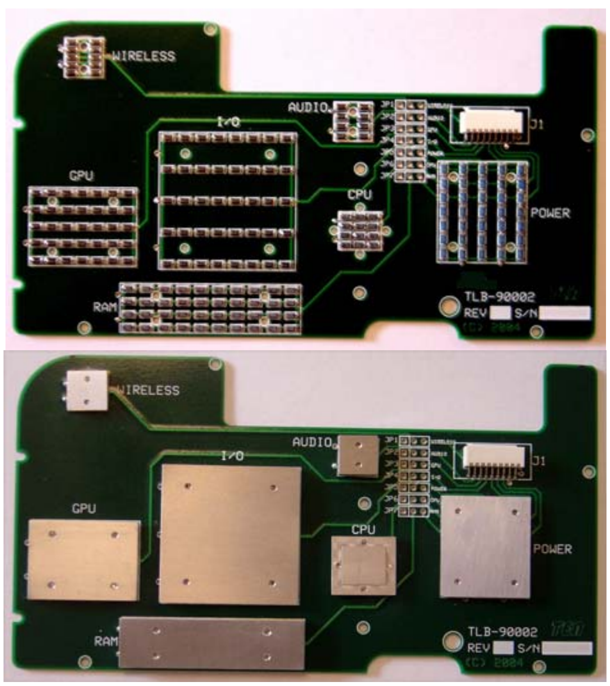

Figure 7 Notebook Computer TLB with and without Heat Spreaders

resistor arrays. The heat spreaders in this case were specially designed to handle repeated removal of a high stiction thermal management solutions – screws were used to hold the heat spreaders in place rather than the usual glue electrically insulated, thermally conductive epoxy.

4. Conclusions

The confluence of greater thermal impact on system performance and product cost, shorter time-to-market requirements and lower development cost objectives have resulted in a greater need for efficiencies in thermal management design. The increasing usage of simulation software to thermally model an electronic system has been helpful in getting system products developed in a more cost-efficient and timely manner. However, too much reliance on un-validated software models can be dangerous as thermal issues continue to grow in importance. Certain tools are necessary to confirm model predictions. And these tools should be in use long before all the components are fully available and a full system design has been completed. Thermal Load Boards is one of these tools which can be designed, fabricated and put into use very quickly (typically less than 4 weeks) and at a moderate cost (in the range of \$6,000 to \$25,000, depending on the size and complexity). The TLB's low turnaround time and fabrication cost offers the potential of modeling and validating several different mechanical configurations while the electronic design is under development.

References

[i] Siegal, B. & Galloway, J., "Thermal Test Chip Design and Performance Considerations", SEMI-THERM Proceedings 2008, March 16-20, 2008, pp 60-63.
[ii] Renz, Marta, "The increasing importance of thermal test dies", Electronics Cooling, September 2000, Vol.6, No.3.
[iii] Nair, Rajesh, "Early Warning Is In The Air For Effective Thermal Management", Electronic Design, July 7, 2008, ppg 73-74