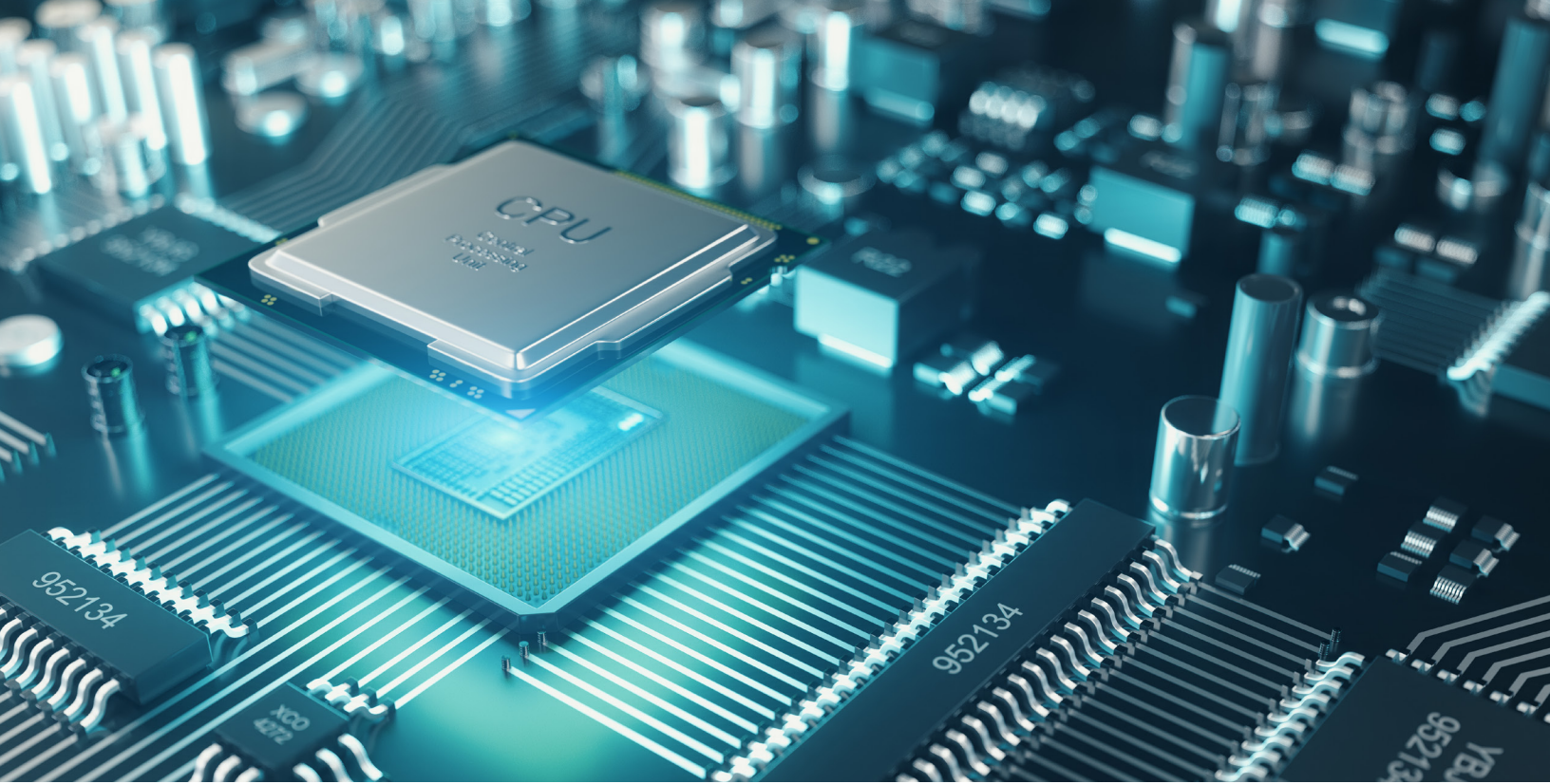




DIGITAL INDUSTRIES SOFTWARE

Ten tips for predicting component temperatures

A high-level how-to guide

Why is component temperature prediction important?

Component temperature prediction is important from a number of points of view. Historically component temperature has been correlated with reliability, with early studies relating field failure rates to steady-state component temperature. More recently, physics-based reliability prediction has related failure rates of electronic assemblies to the magnitude of temperature change over an operational cycle (power-on, power-off, power-on...), and rate of temperature change, both of which are influenced by steady-state operating temperature.

Electronics failures are often attributed to solder joint fatigue at the package-board interconnect. In some applications, like computing, where performance is key, speed is adversely affected by temperature. In other cases components have to run at very similar temperatures to avoid timing issues. High temperatures can cause operational issues, such as latchup. Whether the intention is to increase reliability, improve performance, or avoid problems during operation, accurate prediction of component temperatures helps thermal designers to achieve their goals.

Maximizing certainty in component temperature prediction

Reliable, accurate prediction of component temperatures allows designers to understand how close the design values come to the maximum allowable* temperature. This white paper discusses how to achieve high fidelity component temperature prediction across the design flow, and to gain increased confidence in the final simulation results.

1: Model key components explicitly

It is perhaps self-evident that in order to accurately predict a key component's temperature the component should be modelled explicitly as part of the thermal simulation. However, not all components need to be modelled, and it is often impractical to do so. Small components with a low power density that are not particularly thermally sensitive can be regarded as thermally benign, and do not need to be represented discretely. Heat from these components can be added as a background heat source applied over the whole board, or as a footprint heat source on the board. Simcenter provides filtering options to do this automatically in late design when the populated board layout is imported from the EDA system.

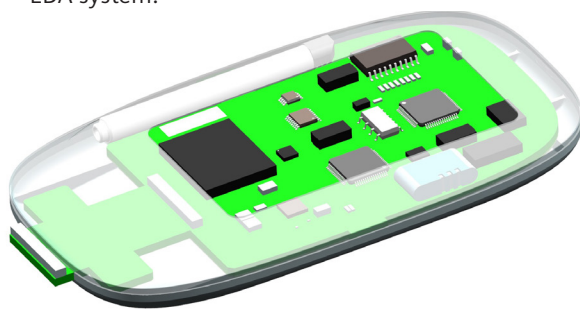


Figure 1: Thermal model of an insulin pump, with components modelled in different levels of detail.

Larger components may disrupt the air flow, requiring them to be represented directly as 3D objects. One class of component that can fall into this category are electrolytic capacitors, used for example in power supplies. These are thermally sensitive, with a low maximum allowable temperature. Modelling electrolytic capacitors explicitly can help ensure their maximum temperature is not exceeded¹.

Large, high-power components and components with high power density will need to be modelled discretely, as their thermal management and their influence on neighbouring components is important to the overall thermal design of the product.

2: Use good power estimates

As noted above, part of the decision as to whether it is necessary to represent a component directly depends on its power density, which is the component power divided by its footprint area.

It is worth re-checking decisions about which components to model discretely as the design evolves, and more information becomes available. In early design it may only be possible to use the maximum rated power for the component in place of an estimate of the likely power consumption. Power budgets for individual components, and for the board as a whole, can change over the course of the design, so these need to be re-checked on a regular basis.

Power estimates for components can be obtained using for example Siemens EDA's Xpedition AMS, which extends electronic circuit simulation beyond standard time and frequency domain analyses to include advanced performance simulations and virtual in-system verification in the Xpedition PCB design flow, including electrothermal simulation.

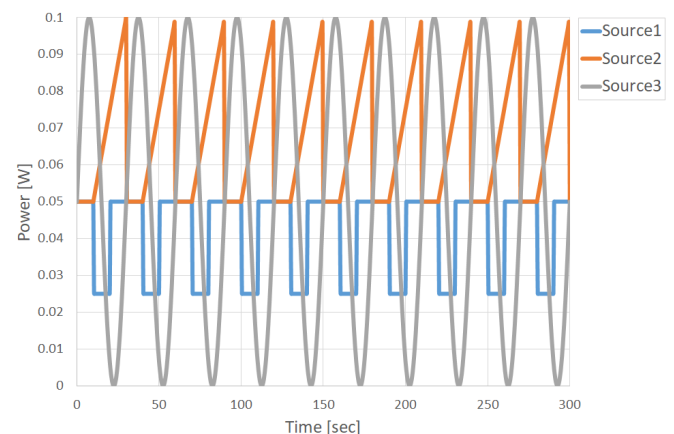


Figure 2: Example power vs. time profile

* Which could be a junction or case temperature, as specified in the component's datasheet.

3: Use the right package thermal model

Component thermal models were introduced in our whitepaper “10 Tips for Streamlining PCB Thermal Design”². The choice of component thermal model depends on several factors.

In early design before the board is routed, or the number of layers in the board is known, accurate component temperature prediction is simply not possible, so a thermally-sophisticated model of the component is not called for. Later in the design, when the model of the PCB can be refined, the component thermal model should also be refined.

Choices about the most appropriate component thermal model are iterative, as components that are predicted to be hot* self-indicate the need to both refine the component’s thermal model and to perhaps consider a component-specific thermal management solution. The board design can form part of that thermal management solution, for example through the use of thermal vias to conduct heat to a buried ground plane.

4: Use compact thermal models from early design

Reference 2 discusses the need to model components accurately and use a 3D representation of the component in the thermal design before package selection. 2-Resistor and DELPHI compact thermal models were introduced. Here we discuss in more detail the predictive accuracy of these and other thermal models.

2-Resistor Models

As noted, a 2-Resistor compact thermal model (CTM) is the lowest fidelity model that is capable of predicting both case and junction temperatures. One benefit is that it does not require any more mesh than a simple conducting block, so using 2-Resistor models has no negative impact on simulation time. Although this has the lowest computational burden, the worst-case error in junction temperature prediction can be as high as $\pm 30\%$ and varies with both package type and package size.

The junction-to-case resistance and junction-to-board resistance thermal metrics this model is based on are measured under standardized conditions.

* In early design ‘hot’ will be in the context of quite a wide design safety margin.

The JEDEC Standard JESD15-3 requires the junction-to-board resistance to be measured on a 2s2p board with continuous power and ground planes. The junction-to-case resistance is measured by pressing the top of the package against a cold plate. As a result, the predictive accuracy of the 2-Resistor model is higher the more closely the application resembles the test conditions. For the junction-to-case resistance, the application environment that most closely corresponds to the test environment is when the component has a heatsink that covers the whole of the package surface. For this reason 2-Resistor models can be used to initially assess the size of heatsink required.

Note that the top surface of a 2-Resistor model is an isothermal node representing the case, so that the base of the heatsink will be held close to isothermal. A 2-Resistor model can therefore be used to determine the number of fins, fin thickness, and fin height needed to reduce the air-side thermal resistance of the heatsink, but not the base thickness needed to adequately spread the heat to ensure that heat passing to the outer fins is not overly restricted.

RC-Ladder Models

For packages that have a single heat flow path, such as LEDs and TO-style packages, there is a JEDEC standard approach³ for measuring a thermal resistor-capacitor model of the heat flow path from the junction down to the package tab. Note that this method does not directly provide a thermal resistance to the exposed top surface of the package. However, provided this can be estimated by some means, Simcenter Micred T3STER hardware can be used to create an RC-ladder thermal model that takes this into account.

Simcenter Micred T3STER is the industry-leading solution for measuring packaged ICs to create these thermal models, which can be used directly as a Network Assembly in Simcenter Flotherm. Unlike 2-Resistor models which only contain thermal resistors, these models include thermal capacitors, and so can be used for transient simulations. These models can give excellent results when the application environment is close to that of the test cold plate environment, e.g. when the package is soldered to a MCPCB or a copper pad on a high conductivity board.

DELPHI Models

DELPHI models are so-named as they originated from the DELPHI Project coordinated by Flomerics Ltd. in the late 1990s. These models have partitioned top and bottom surfaces, with a matrix of thermal resistors to connect these surfaces to the junction and/or to one another. These additional internal thermal resistors allow the heat flow through these paths within the package to adjust depending on the boundary conditions, and in many applications the model will predict the junction temperature accuracy to well within $\pm 10\%$, being a worst-case figure. In general DELPHI models are adequate for detailed thermal design work of all but the most thermally-critical packages, stacked or 3D ICs, or where additional information is needed from the simulation, e.g. the temperature distribution on the die surface. Like 2-Resistor models they also only contain resistors, so can only be used for steady-state simulation.

Detailed Models

Detailed models are thermal models which discretely model all the thermally-relevant features of the package internals. Note that these models often contain some degree of approximation, as features such as individual bond wires and solder balls are often lumped together. However, the aim of such models is to allow the temperature distribution within the package to be accurately represented. Provided that the geometry and material properties used are correct, such models offer the highest fidelity.

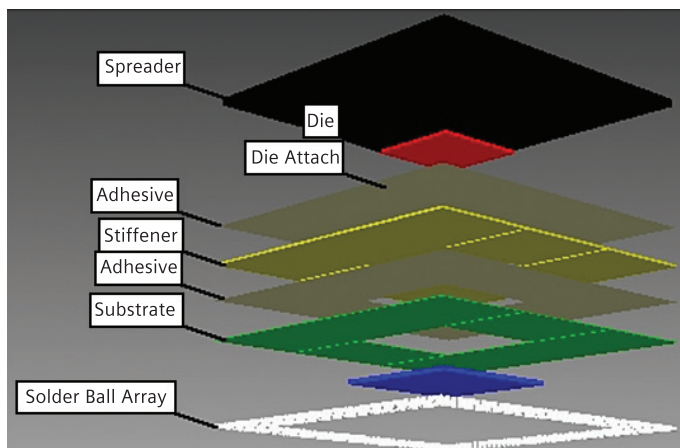


Figure 3: Thermally detailed thermal model of a chip package.

Components that require specific thermal management solutions, such as a heatsink, fansink, or thermal pad should be modelled in detail in order to correctly optimize the cooling solution. For example, in the case of a heat sink it has long been known that the temperature distribution in the package influences the temperature distribution in the heatsink base, and vice versa⁴. Consequently, detailed package thermal models are recommended for such purposes.

Another advantage of detailed models is that they allow the temperature of the solder interconnect to be predicted. Thermomechanical shear, coupled with temperature change, is the primary stressor affecting solder joint life.

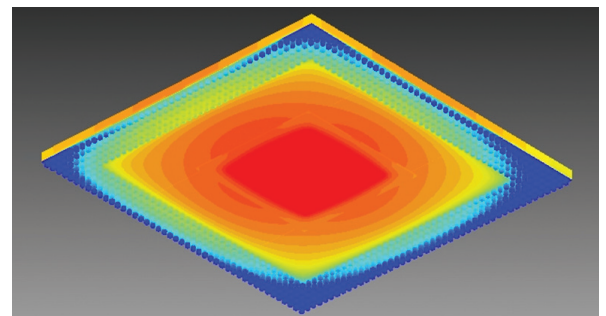


Figure 4: Temperature distribution on underside of a BGA package showing individual solder balls

BCI-ROMs

A recent advance in predicting component temperatures is through the use of reduced order models, or ROMs. ROMs can now be created that are independent of their boundary conditions (BCI), rather than specific for a given thermal environment⁵. That means that BCI-ROMs can be created by package vendors, independent of their thermal environment, and provided to end users for use in simulating a specific thermal environment. They are available in a variety of formats: as raw matrices, SPICE, VHDL-AMS and FMU. There are now a range of authoring options for BCI-ROMs within Simcenter.

BCI-ROMs have other very desirable characteristics:

- They are highly accurate, with the accuracy defined as part of the creation process (typically > 98%)
- Support multiple heat sources
- Support all transient timescales
- Hide sensitive IP as the internal geometry of the parent detailed model from which they are derived can not be reverse engineered from the ROM
- Report the appropriate junction temperature defined by the vendor, without the vendor having to reveal where within the model that is.
- Solve orders of magnitude faster than detailed models⁶

A major advantage of this is that they can be included in circuit simulators, like Xpedition AMS and PartQuest Explore, allowing circuit simulators to be 'temperature aware', which is key to getting accurate power estimates in early design.

Use of BCI-ROMs within 3D CFD simulators has the potential to be a game-changer in the supply chain for package thermal models, and BCI-ROMs can also be created for whole boards.

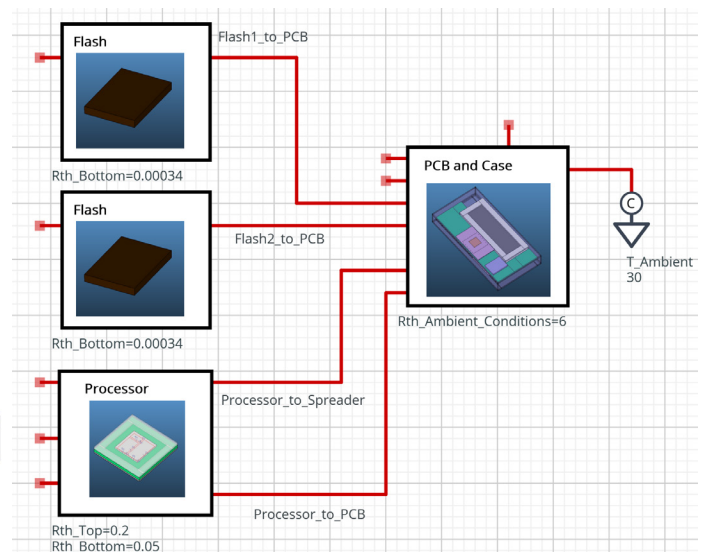
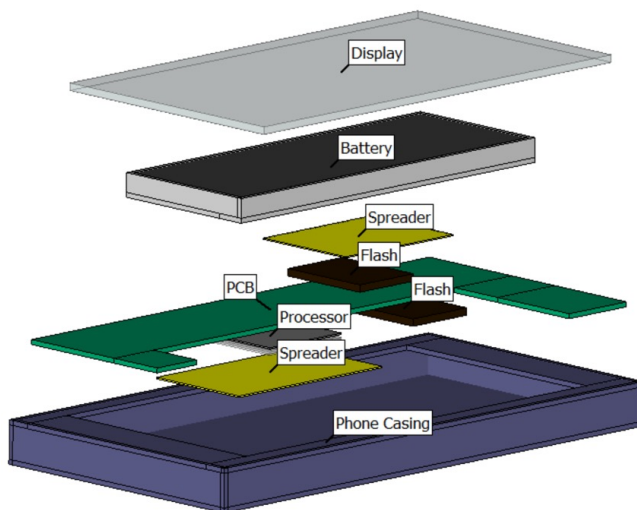


Figure 5: BCI-ROMs of key components in a mobile phone in PartQuest Explore

5: Create your own models as required

In practice, the choice of thermal model may largely depend on what is available from the vendor. Even today we find vendors may only supply information in the form of a data sheet, e.g. as a PDF, and these may not contain the information necessary for even basic thermal design. For example, the data sheet may contain only a junction-to-ambient thermal resistance which can't be used for design, only performance comparison. JEDEC has published

JEP181⁷, a standard file format for thermal simulation data exchange. It is XML-based, using ECXML developed by Siemens, short for 'electronics cooling extensible mark-up language'.

Simcenter Flotherm is the industry-leading electronics cooling software, and the Simcenter Micred T3STER hardware is widely used by semiconductor companies and packaging houses to characterize their products. There are more thermal models available for use in Simcenter Flotherm, Simcenter Flotherm PCB and

Simcenter Flotherm XT than any other thermal design tool, with thermal models available from many leading vendors. Around 30% of the customer base for Simcenter Flotherm PACK are users at IC package vendor companies. The majority of users are at end-user companies, creating their own representative package thermal models.

For a system integrator responsible for accurate component temperature prediction, Simcenter Flotherm PACK (as a SaaS solution) and Simcenter Package Creator offer the ability to create thermal models for use at various stages in the design

flow – 2-Resistor, DELPHI and detailed – based on common input data. The tools are wizard based, with intelligent default values, allowing a minimum amount of effort to be expended to get a representative model, which can then be refined as new information becomes available.

Simcenter Flotherm PACK's worksheet for each package style can be provided to a supplier to show what information is needed to create a thermal model of their part if they don't already provide one.

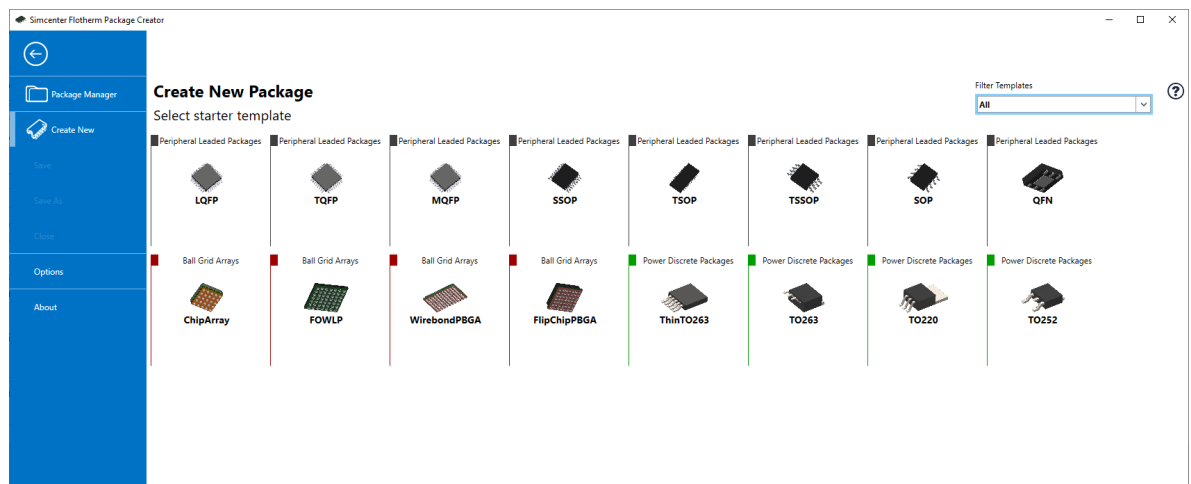


Figure 6: Simcenter Flotherm Package Creator

6: Use power maps

As dies get thinner, temperature variation across the die surface increases, as the die itself becomes less effective as a heat spreader. As a consequence, it is becoming more common to consider junction temperature not as a single number, but something that varies over the surface of the die even in single die packages. The latest advanced package designs of 2.5D chiplet-based and 3D packages are far more complex, lending them more suitable for representation as BCI-ROMs that capture their thermal complexity.

When using compact models, junction temperature is considered a single value, and the model, if provided by a vendor, should provide the number that is appropriate to compare against the specified maximum

allowable junction temperature. In general, it is the maximum junction temperature that has to be limited. The vendor should also make it clear how to obtain that number from the simulation. So if it is a junction temperature, where on the die surface that should be measured.

Detailed models predict the temperature variation throughout the package, including the die. To accurately predict the temperature distribution on the die, it is necessary to account for the active power variation over the die's active surface. For more complex die (e.g. System-on-Chip) this is often a function of what the die is doing, so a die may well have several power maps associated with it. In addition to this there is the leakage power which is a function of the local temperature, and hence exacerbated by the active power.

Power maps can be exported from power analysis tools such as mPower and may be available as a comma separated variable (CSV) file. These are often coarsened by the vendor to provide a power map with typically up to ~50 different power regions but can be many more.

Monitor points should be used to monitor the temperature of the centre of the region(s) found to have the highest temperature from a steady-state simulation with each power map.

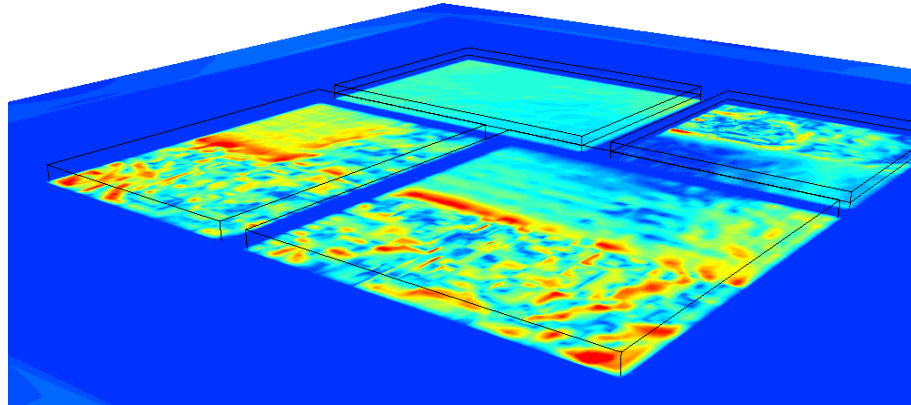


Figure 7: Detailed model of a multi-chip package with die power maps

7: Validate detailed models with experiments

Transient thermal testing techniques allow the effective thermal resistances and capacitances in the model to be calibrated against experiment.

Such uncertainties can be addressed by using Simcenter Micred T3STER to measure the response of an actual package, and then adjust the properties of the simulation model to fit the experimental response. By doing so, the junction temperature rise within the package can be predicted to within just a few per cent for all boundary conditions and at all times during a transient simulation. This represents the pinnacle of package thermal modelling, and the

process of model calibration is fully automated within Simcenter, requiring the user only to nominate what parameters to vary and the permitted range of values.

In the case of very high power packages such as IGBTs and MOSFETs used in energy conversion applications thermal characterization may be done most conveniently in a Simcenter Micred Power Tester, which combines thermal characterization with active power cycling for reliability prediction and failure mode detection for this class of devices.

For package designers, a validated detailed thermal model, which can also be delivered as a BCI-ROM, is a pre-requisite for subsequent improvements in design,

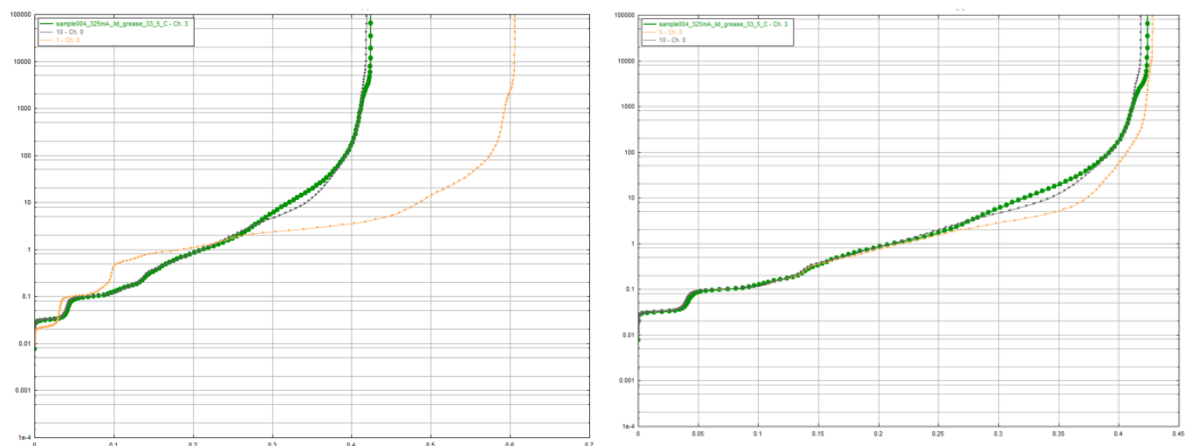


Figure 8: Initial (left) vs. Final (right) Structure Function Fits for a Package⁸.

materials, and processing, and is essential for finite-element based stress prediction by ensuring the correct temperature distribution within the package and hence it's warpage and structural interaction with the PCB.

For package designers, a validated detailed thermal model, which can also be delivered as a BCI-ROM, is a pre-requisite for subsequent improvements in design, materials, and processing, and is essential for finite-element based stress prediction by ensuring the correct temperature distribution within the package and hence it's warpage and structural interaction with the PCB.

From an end user's perspective, a validated detailed thermal model or BCI-ROM is the best starting point for any custom heatsink design.

8: Design custom heatsink solutions

Up to this point a standard design of heatsink will have been selected to ensure that the component can be adequately cooled, however this may be a sub-optimal solution.

The purpose of custom heatsink design optimization is to maximize the heat transfer for the minimum system pressure drop and wake region formed behind the heatsink. The contact area between the heat sink and the package body can also be optimized to prevent heat spreading in the base of the heatsink and then flowing back into the package body around its periphery.

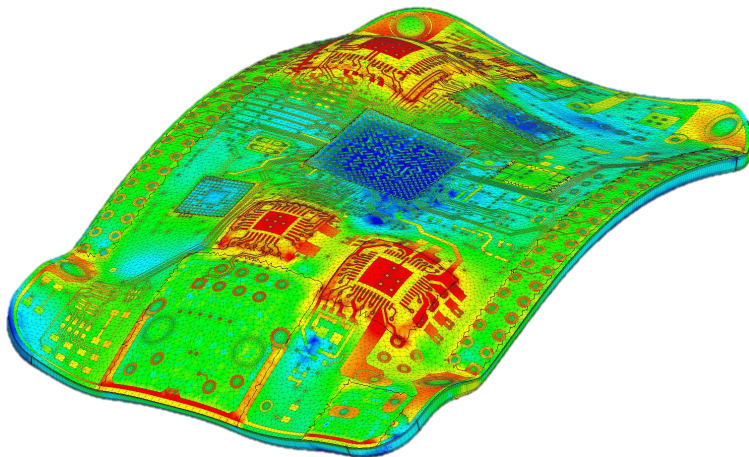


Figure 9: Von Mises stress caused by thermomechanical effects in a PCB with amplified out-of-plane displacement simulated in Simcenter FLOEFD.

Note that because the major heat flow path out of the package will be into the heat sink, designing a custom heat sink can start before the board is routed. This is important as real estate on the board surface may need to be reserved for the heatsink attachment, and so is affected by the size of the heatsink base. Failing to design or select an appropriate heatsink before routing starts risks at least one PCB design re-spin.

9: Accurately capture thermal interface material resistance

Thermal Interface Material (TIM) thermal conductivity can be accurately measured as a function of temperature with Simcenter Micred TIM Tester⁹, allowing the most suitable TIM material to be chosen for a particular application e.g. between a component and a heat sink. Depending on the material chosen, how well this wets the surfaces depends on many things, such that the total thermal resistance including the interfacial resistances on each side of the TIM. It is worth noting that the thermal resistance of the TIM can be a substantial contribution to the junction temperature rise, and so accurate data for the overall TIM thermal resistance is important for accurate component temperature prediction.

10: Provide accurate temperatures for mechanical stress prediction

As IC packaging challenges continue to increase, package vendors are finding the need to design for thermally-induced stresses that more closely match those the part will experience in the application environment.

Simcenter provides efficient workflows for temperatures and thermal model geometry to be used for finite-element analysis providing the thermal strain as a boundary condition for the stress calculation. Within Simcenter, temperatures are intelligently mapped onto the finite element mesh accounting for differences in the shapes of the geometric objects that might exist between the two analysis disciplines. The assembly under consideration can for example include the package, heatsink if attached, and a section of the board onto which the part is soldered.

From an end user's perspective, a validated detailed thermal model or BCI-ROM is the best starting point for any custom heatsink design.

| Concluding remarks

This whitepaper provides an overview of the key considerations in component temperature prediction. It is by no means exhaustive, with many details not covered. If you are responsible for ensuring component temperatures do not exceed specified limits and want to know how Simcenter thermal design software can help, and what is the right product for your application, then please contact us through the Simcenter web page <https://www.siemens.com/simcenter>

Acknowledgements:

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Dr Robin Bornoff

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