

Overall Thermal Simulation of Electronic Equipment

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Abstract

This paper describes an overall approach for the thermal simulation of electronic equipment based on the cooperation between software dedicated to board design, computational fluid dynamics (CFD) simulation and board thermal analysis. The board geometrical description, as created by the CAD system, is shared by the board simulator and the CFD package, whose role is the characterization of the global 3D thermo-hydraulic behaviour of the electronic system and the accurate specification of the boundary conditions at the vicinity of the boards to analyse. The board analysis plays the central role with respect to the determination of junction temperatures and special attention is paid to component model elaboration. An example illustrates the proposed approach.

1.0 Introduction

In the thermal management of electronic systems, board analysis currently plays the central role, by allowing in particular the determination of the component junction temperatures to point out the overheating problems which may lead to equipment malfunction. Basically, a board analysis mainly consists of solving the heat equation to characterize the conductive effects which spread the heat locally dissipated by components prior to its evacuation through the board environment. Accordingly, an accurate representation of the board constitution is a fundamental requirement for obtaining reliable thermal results.

This requirement implies that it is necessary to specify the boundary conditions with an accuracy level consistent with the high precision methods available for the heat equation solving. This specification may be difficult, since the local environment of a board is actually related to the global behaviour of the system (rack, cabinet) in which the board operates. This behaviour is hard to predict for geometrical and thermal reasons. Geometrically, the internal obstacles (deflectors, grids, stiffeners...) have a strong

three-dimensional influence on the fluid flow. Thermally, natural convection cooling illustrates for instance how complex the interactions between the local and global viewpoints may be, since in this case the heat dissipated by components gives rise to the flow motion, while this motion governs the heat removal. The proposed approach is thus first characterized by links set up between software respectively dedicated to board design, system CFD (computational fluid dynamics) simulation and board thermal analysis.

To perform the CFD simulation, boards have to be represented in a simplified manner and a similar principle is applied to components for the board thermal simulation. From the structural viewpoint, components are indeed complex structures and a detailed representation of those at a board analysis level would lead to excessive problem sizes. This means that components need to be replaced by macro-models which play an important role in the thermal simulation of electronic systems. The method followed to obtain such models is the second main feature of the approach proposed.

The approach description is finally illustrated through an example showing the same board viewed from each piece of software.

2.0 Software cooperation

The board playing the central role in the proposed approach, the board design system can be considered as the starting point (Fig. 1). With the component placement determined, the board placement in the system is performed. This operation consists of exporting the data describing the board constitution to the CFD package and specifying the board spatial location within the equipment. Control may also be applied to the board modelling. Basically, boards become impervious plates whose sides dissipate flux to the fluid. By default, the flux distribution is uniform and obtained by adding up the power generated by the components mounted on the corresponding side.

This distribution may be refined by defining subareas, each characterized by its flux generation.

The user then provides the complementary data such as the geometrical elements other than boards (power supply unit, deflectors, grids, internal obstacles...) as well as the conditions expressing the operating mode of the system (fan characteristics, fluid inlets and outlets,...). Since these conditions are applied to a physical system whose boundaries are the actual limits of the real equipment, they are closer to the designer's view than the ones applied to a board.

The fluid flow 3D simulation is then processed and result inspection allows a decision on which boards may overheat due, for instance, to stagnation zones. The flow characteristics at the vicinity of the selected board sides, consisting mainly of the temperature, velocity and heat transfer coefficient fields, are then exported to the board thermal simulator.

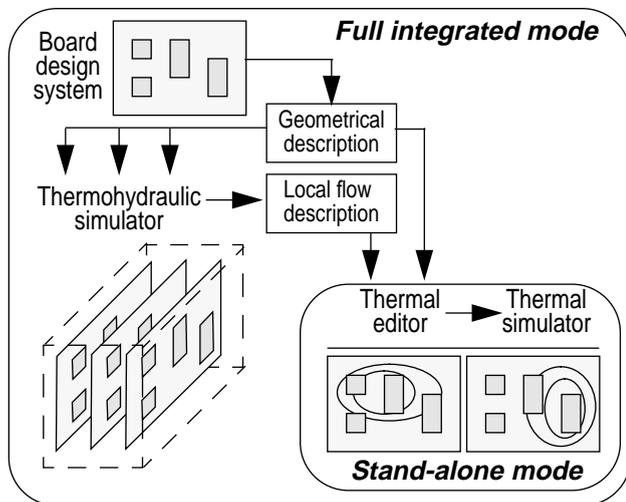


Figure 1. Software cooperation overview

For that purpose, the Thermal Simulator is equipped with a gateway named the Thermal Editor, whose input file is block-structured. One sub-block of this file allows the CFD results to be loaded.

These become the data allowing the set up of the boundary conditions for the board thermal simulation, which also shares the board geometrical description with the CFD package. It is important to notice that a given board may appear several times in the equipment. Although identical from a geometrical viewpoint, such boards become distinct instances because of the local nature of flow characteristics. Such situations emphasize the need to manage software cooperation in an appropriate framework whose practical importance is clear, although its description is beyond the scope of this paper. Globally, this framework uses a *Controlled Directory Structure* to manage the files ensuring the links between applications,

these latter being themselves driven from a *System Interface*.

At the board simulator level, the flow results (temperature and heat transfer coefficient fields) are sufficient to completely describe the board environment. However, as pointed out by [1], the characterization of the heat transfer between boards and fluid flows is still an open subject. This difficulty is related to the very complex disturbances induced by components on the fluid flow. Thereby, this latter may significantly differ from the flat plate flow considered in the open literature for the conventional heat transfer coefficient correlations. To ease this difficulty, the final results transmitted by the CFD package also include the velocities so that the user can choose to use his own set of correlations.

The board simulation then allows the accurate modelling of the conductive effects to compute the component junction temperature to determine whether the system thermal design is correct or not. With such a global thermal simulation, the user can not only detect if excessive hot spots may lead to system malfunction but also overcome the tendency to over engineer by using, for instance, larger and noisier fans than required. The board simulation also shows how the power is evacuated from the components to the environment, especially the cooling fluid, allowing if required the refinement of the board model in the CFD package by a feedback loop.

This simulation is performed using a conventional finite-difference approach based on a 2.5D geometrical board model. This approach has some limitations with respect to a 3D finite-element model, but it has also interesting features. Firstly, the meshing time is shorter, and same remark applies for the execution time, since there is no numerical integration on each element. Secondly, the insertion of component models in the board model is simpler. Thirdly, using the thermal-electrical analogy, the user handles concepts he is familiar with.

The gateway attached to the thermal simulator allows not only the importation of the board geometrical description, but also its full creation. This gives the possibility to perform thermal analysis ranging from full stand alone mode, the whole thermal data being created locally, to full integrated mode, in conjunction with the CAD and CFD applications, intermediate modes being also possible. For instance, when CFD results are not available, the user may choose to use a *heat transfer coefficient advisor*, part of a thermal toolbox included in the Thermal Editor.

The full stand alone mode is particularly useful to rapidly prototype a board design and to quickly characterize its thermal behaviour, even if the placement is not fully completed. It is also fundamental for the creation of component models.

3.0 Component modelling

The basic requirement of component models is to provide junction temperatures. A first-order approach consists of using the junction-to-case data provided by manufacturers. The advantage of such an approach resides in its simplicity and in the wide availability of this data. However, studies [2] [3] have revealed that such models may be inaccurate.

The approach proposed for model creation is introduced by the following remarks. Firstly, the resulting models need to be sufficiently simple, to avoid the generation of an unreasonable problem size at the level of the global board model. Secondly, detailed information on the component thermal behaviour is generally not required. While the junction temperature is of primary importance, the main requirement related to the top package temperature is to give a satisfactory mean temperature for the evaluation of the heat transfer between this component part and the environment. Thirdly, end-users need to be able to produce their own thermal models, to process specific components or to build models suited for their own requirements.

Up to now, there is no general agreement on standard component models and same remark obviously holds true on their creation. The software-based approach considered here employs a structural and thermal description of the component, through a 2.5D description made with the thermal editor. This approach is consistent for the user since the same geometrical tool is used to describe the layers that comprise a board or the cuboids that represent a model. This description is then discretized using the finite-difference mesher of the thermal simulator. Up to this point, there is almost no difference between the simulation and modelling activities, except that the boundary conditions are replaced by modelling directives specifying the future model nodes. Thus, the discretization process results in an algebraic system which expresses as:

$$[G] \{T\} = \{S\} \quad (1)$$

where $[G]$ is the conductance matrix, $\{T\}$ the temperature vector and $\{S\}$ the flux vector. The theoretical reduction principle, based on a condensation procedure similar to the sub-structuring method used to handle large finite element problems [4], can be summarised as follows. System (1) is partitioned as:

$$\begin{bmatrix} G_{mm} & G_{mp} \\ G_{pm} & G_{pp} \end{bmatrix} \begin{Bmatrix} T_m \\ T_p \end{Bmatrix} = \begin{Bmatrix} S_m \\ S_p \end{Bmatrix} \quad (2)$$

where it can be assumed, through a renumbering process, that the last p unknowns are those to be eliminated. Under expanded form, this leads to:

$$G_{mm}T_m + G_{mp}T_p = S_m \quad (3)$$

$$G_{pm}T_m + G_{pp}T_p = S_p \quad (4)$$

Eq. (4) allows the expression of the vector T_p as:

$$T_p = G_{pp}^{-1}(S_p - G_{pm}T_m) \quad (5)$$

Substituting this vector in (3) yields:

$$G_{mm}T_m + G_{mp}G_{pp}^{-1}(S_p - G_{pm}T_m) = S_m \quad (6)$$

or:

$$\left(G_{mm} - G_{mp}G_{pp}^{-1}G_{pm} \right) T_m = S_m - G_{mp}G_{pp}^{-1}S_p \quad (7)$$

So, system (1) of size $m+p$ is replaced by the new system $[G]^* \{T\}^* = \{S\}^*$ of size m with:

$$G_{mm}^* = G_{mm} - G_{mp}G_{pp}^{-1}G_{pm} \quad (8)$$

$$S_m^* = S_m - G_{mp}G_{pp}^{-1}S_p \quad (9)$$

The conductances contained in the reduced matrix G_{mm}^* are the local network data constitutive of the component model. This network can be viewed as a means to distribute the power dissipated in the junction among the various parts of the component through which heat is removed. This is illustrated by the simple typical model depicted in Fig. 2.

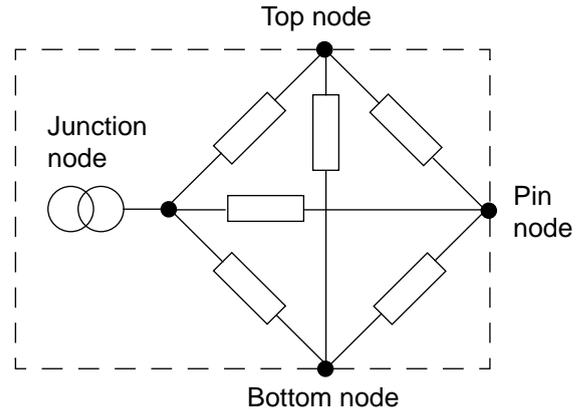


Figure 2. Four-node component mode

If required, much more complex models can be set up, especially when the component dimensions are large. When completed, a thermal model can be stored in a dedi-

cated library or loaded in the simulator input stream. For that purpose, the modeller output has exactly the same format as the simulator input.

During a simulation, the role of the thermal mesher is to connect the model outer nodes to the board and environment nodes, through conductances expressing the heat transfer modes involved. Node B^- is for instance connected to a board node through a conductance representing the eventual mounting gap located under the component. Similarly, node B^+ is connected to an environment node through a conductance modelling the convective and radiative heat transfer with the top part of the component. When the board simulator is used in conjunction with the CFD package, the temperature of the environment nodes are obtained by a spatial interpolation of the fluid temperature field.

Thus, schematically, the main difference between simulation and modelling is that instead of solving the algebraic system expressing the thermal balance to get the temperature maps, this system is processed to express the thermal balance between a reduced number of nodes.

4.0 Simulation example

The proposed approach is applied to a rack whose dimensions are 428×350×444mm (Fig. 3).

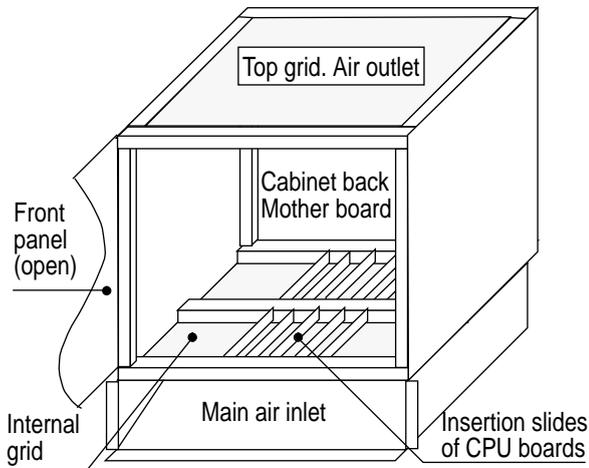


Figure 3. Enclosure geometry

This device, cooled by natural convection with air at 24°C, encloses two single-sided CPU boards inserted in slides and a mother board. One of these CPU boards is dissipating 5.2W and is equipped with thermocouples allowing the measurement the package top and pin temperatures of certain components, as well as the temperature of the board surface at ten locations labelled L1 to L10 (Fig. 4). The board is made of epoxy glass ($0.24 \text{ Wm}^{-1}\text{C}^{-1}$) and its dimensions are 324×292×1.6mm. 135 components are

mounted on it, mainly of DIP type, with a mounting air gap of 0.4mm.

The results obtained during a steady-state analysis are given in Table 1. Fig. 5 and Fig. 6 give the flow within the enclosure and the isotherm lines respectively generated by the CFD and board analysis softwares. These lines in particular reveal how the hot spot is shifted upwards due to natural convection effects, which illustrates the benefit of a CFD simulation. [5] gives another application example where the comparisons are based on the component junction temperatures.

Components				Board		
Location		Exp.	Sim.	Loc.	Exp.	Sim.
U3	Top	38.4	36.8	L1	34.9	32.2
U11	Top	39.3	34.6	L2	33.2	31.7
U14	Top	51.5	52.3	L3	29.7	30.2
	Pin	39.5	35.2	L4	29.3	32.2
U20	Top	30.4	28.1	L5	29.1	31.9
	Pin	29.7	29.4	L6	27.4	29.8
U44	Top	41.8	44.1	L7	26.9	29.5
	Pin	33.5	32.8	L8	25.6	28.7
U45	Top	37.3	39.7	L9	25.4	28.1
	Pin	29.6	31.1	L10	25.1	28.4
U136	Top	35.6	36.0			

Location: see Fig. 4
Exp.: Experimental results (temperatures in °C)
Sim.: Simulation results (temperatures in °C)

Table 1. Component and board comparative temperatures

5.0 Conclusion

The approach proposed to characterize the thermal performances of an electronic system is centered on a board simulator whose main features can be summarized as follows. The geometrical domain is the board description created by a dedicated thermal editor or imported from the board design system. This finite-difference based simulator mainly solves the conductive heat transfer within the boards, in steady-state or transient modes. The thermal loads induced by components are taken into account through local networks, obtained by a condensation procedure applied to a discretized network elaborated through a structural description of the component. The boundary conditions may be imported from a CFD package allowing loading of board descriptions from board design system and export of the local flow characteristics in the vicinity of a board.

These features give the designer a maximum flexibility to perform thermal analysis ranging from preliminary studies to full electronic equipment analysis.

6.0 References

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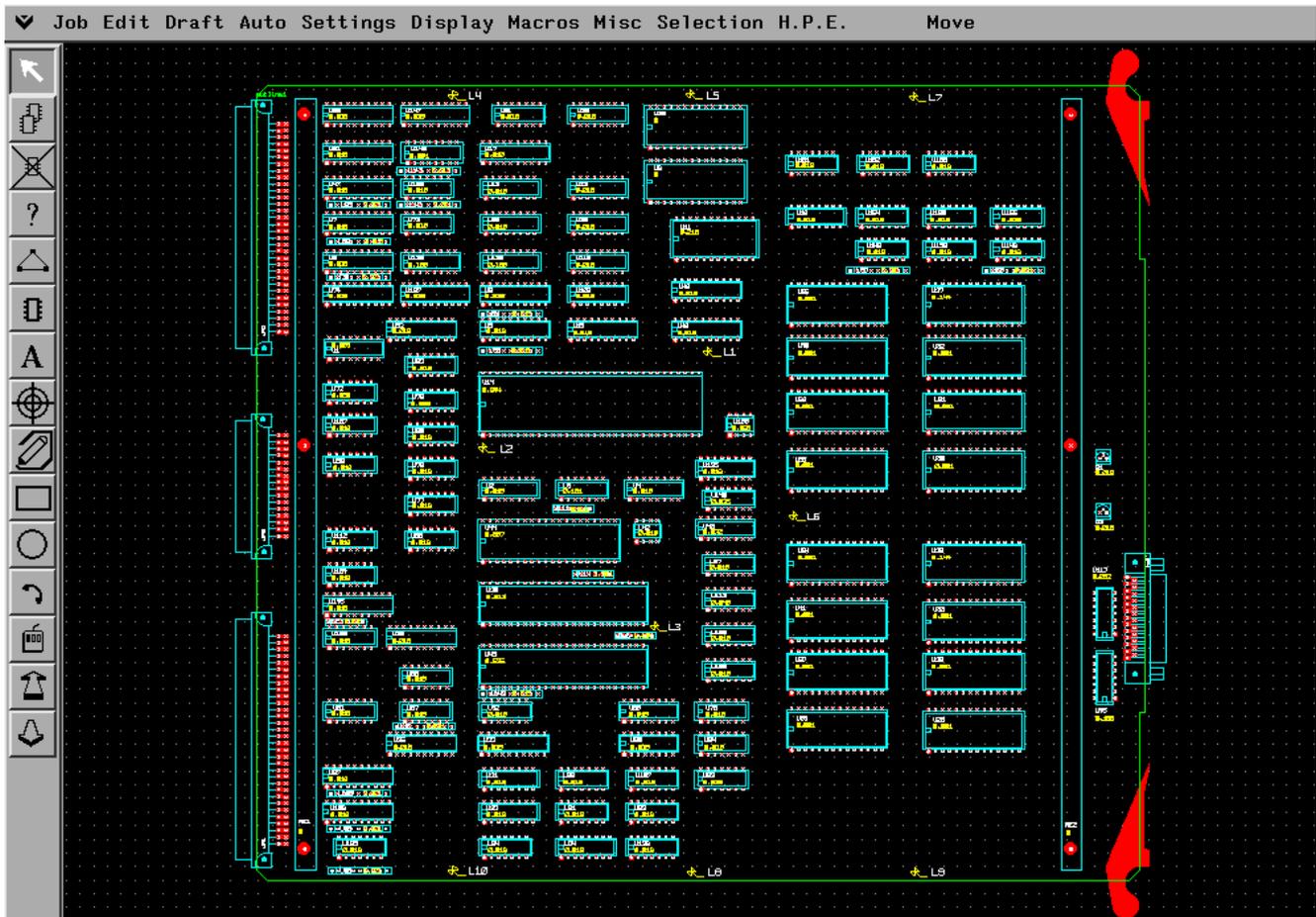


Figure 4. Board geometry (board design system)

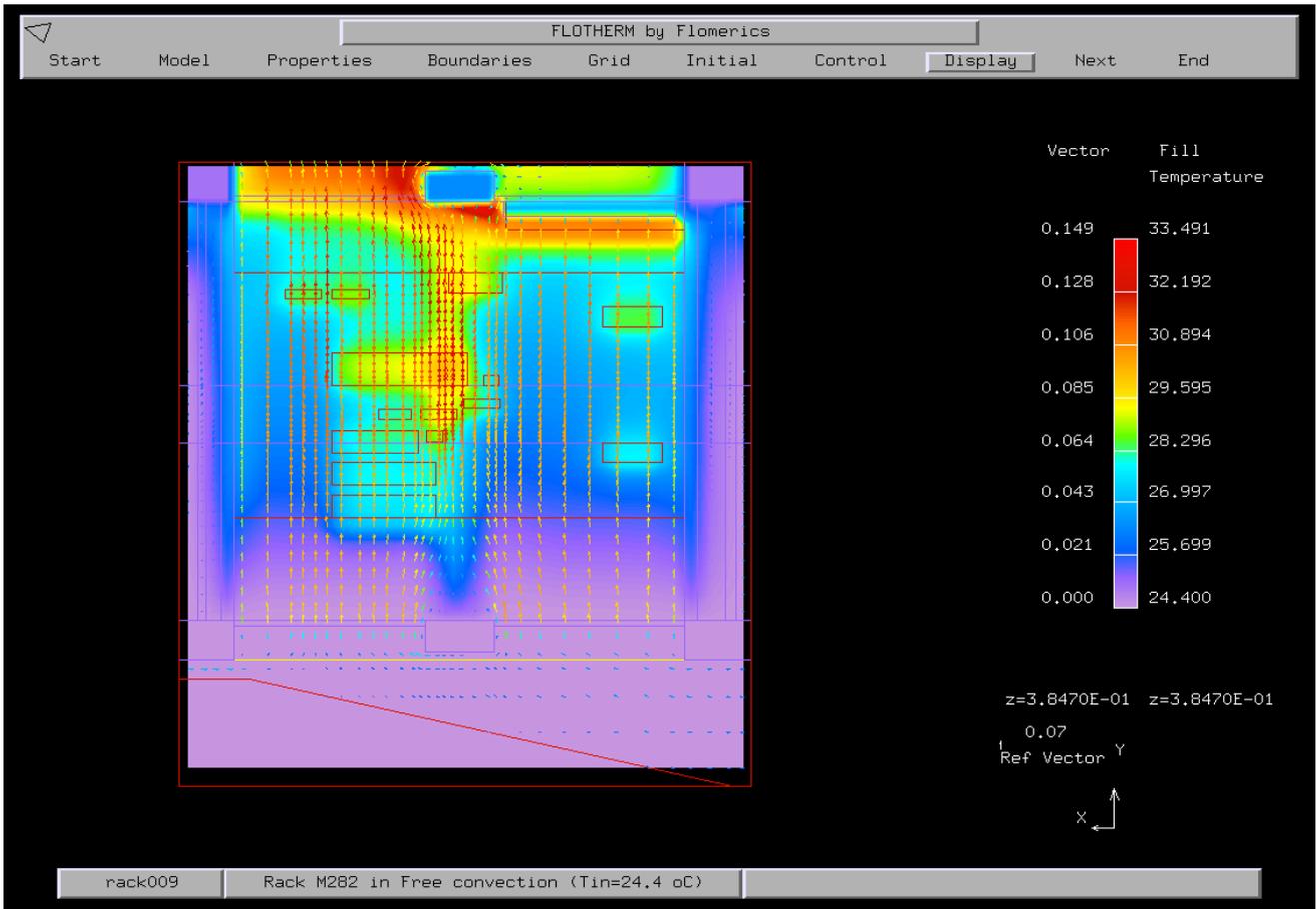


Figure 5. Velocity map. Fluid isotherms (CFD simulator)

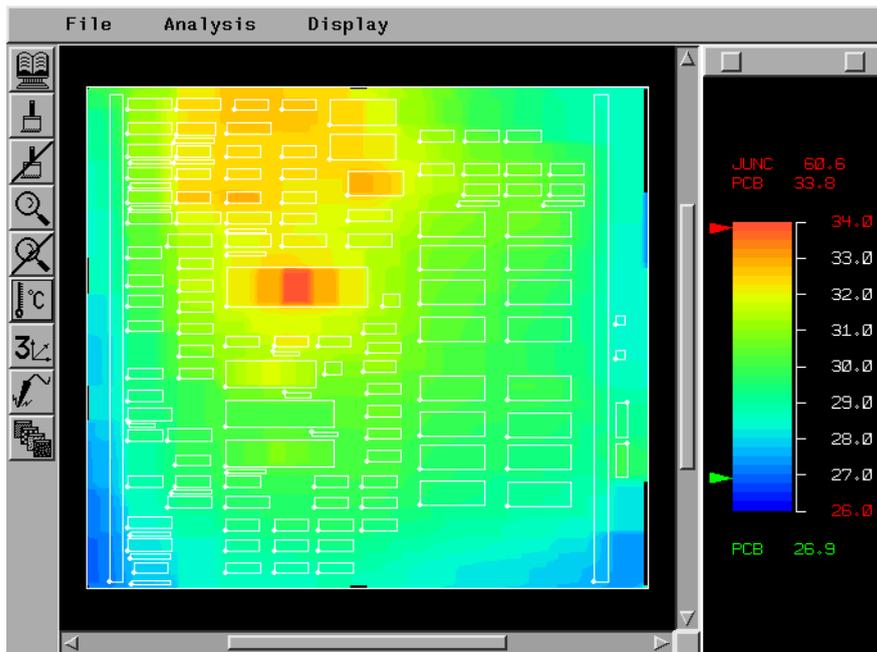


Figure 6. Board isotherm maps (board thermal simulator)