Automated Thermal and Reliability Analysis of Avionics Designs

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This paper describes a new automated process currently being developed and implemented at General Dynamics Convair/Space Systems Divisions to enhance the reliability of printed circuit boards (PCB's). The process is entitled Convair-Computer Aided Reliable Design (C-CARD) and is used to optimize the component mounting locations on a PCB for thermal reliability. PCB information contained in a computer-aided design (CAD) database is used to automatically produce a thermal mathematical model for use with the SINDA finite-difference heat-transfer code. Resulting temperature and reliability predictions are displayed and evaluated by the packaging engineer based on the design requirements. A plot of isotherms on the PCB surface is also determined from the analysis. If necessary, the components are relocated and this procedure is repeated. The isotherm data are used to guide any needed relocation. Once the PCB design is optimized for thermal reliability, it is then released for manufacture. In this way, the heat-transfer analysis is integrated into the design process and provides the packaging engineer with a thermally safe design in minutes instead of weeks.

Introduction

OVER the last several years, thermal control of electronic equipment has become an area of increased importance in military and space applications. The popularity of microcircuit devices has established a need for higher power density printed circuit boards (PCB's) requiring minimal maintenance (i.e., high reliability) and necessitating optimization of thermal control techniques. The reliability of an electrical component is a function, in part, of the operating temperature of that component. Historically, operating temperature has not been considered as an influence in the initial layout of components on a printed circuit board. Consequently, component thermal reliability results from a somewhat random placement of parts on the board.

Minimizing PCB component temperature rise is especially important for microcircuit junctions. MIL-HDBK-217B, "Reliability Prediction of Electronic Equipment," states that the reliability of microelectronics related to junction temperature increases by 20% for each 5°C decrease in junction temperature in the vicinity of 100°C, a temperature typical of military applications. It also states that thermal analysis should be part of the design process and included in all tradeoff studies covering equipment performance, reliability, volume, environmental control systems, etc.

The C-CARD process is an application of this requirement. Since the entire process is interactive, a thermally safe design can be reached quickly and efficiently, reducing the need for costly design changes (caused by insufficient thermal control) after fabrication has begun.

Discussion

State-of-the-art PCB design and manufacture at General Dynamics Space Systems/Convair Divisions uses a Computervision CADDS3 system to create a two-dimensional database during PCB layout. The database is used for numerically controlled fabrication of the circuit board.

This technology is adaptable to automating the construction of a thermal mathematical model based on an electrical analog. The model consists of a series of nodes connected by thermal "conductors." The SINDA finite-difference thermal analysis program is used to solve the network.

The C-CARD design process is illustrated in Fig. 1. It starts in the predesign phase, where the preliminary information is compiled. The electrical engineer generates a circuit schematic and parts list with associated power dissipation. The mechanical engineer provides board size, shape, and support configuration. Also, the thermal analyst performs a preliminary analysis of the entire electronic box to estimate the boundary conditions to be used.

The circuit schematic, parts list, and board data are used by the PCB designer to develop a detailed design of the board with a Computervision CADD3 system. The database created contains all the information necessary to fabricate the board. PCB computer-aided design (CAD) engineers assign the necessary thermal attributes for each board component to specific "T" (text) nodes in this database. The entire database is written to a Computervision (CV) SAVFIL tape. The CV tape is loaded into the CDC 855 (Cyber) system, the large mainframe computer for systems analysis.

A program is subsequently run on Cyber to sort through the database and extract, in a readable format, the location and thermal data for each component. The information extracted includes location of the component with respect to the origin of the board (see Fig. 2), component dimensions, orientation, dissipated power, lead resistance, case-to-junction resistance, and contact coefficient. A file containing this information is output and used as part of the input to the "AUTOMOD" thermal model generation program. The remainder of the input is generated by the user, who is prompted to provide boundary conditions, physical conditions, and model parameters to describe the board.

The input file, now complete, is used by AUTOMOD to generate a thermal mathematical model of the PCB with appropriate boundary conditions and simulated operating environments. Details of the AUTOMOD program, which is the heart of the process, are described below. The model is based on an electrical analog and consists of a grid of nodes, with detail level specified by the user and a network of ther-

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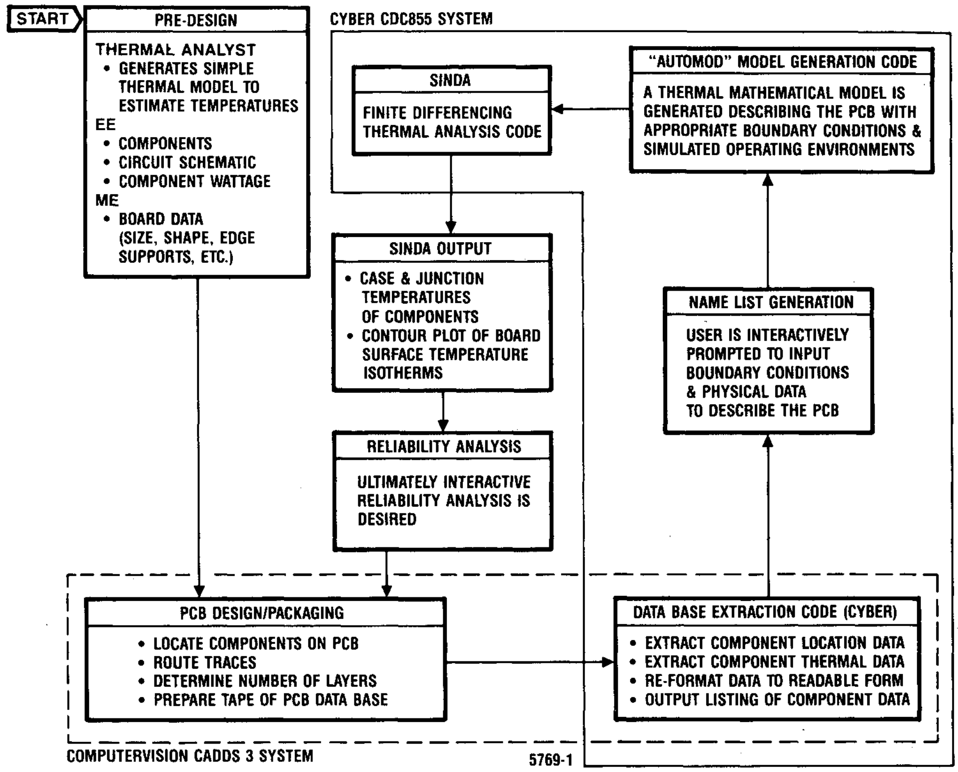


Fig. 1 C-CARD design process.

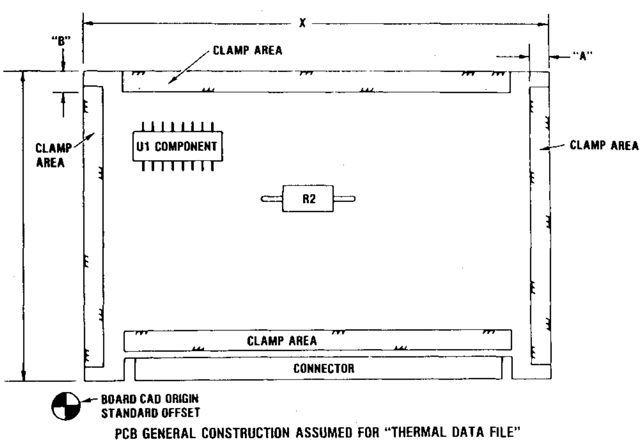


Fig. 2 Extracted component data.

mal conductances connecting the nodes (see Figs. 3 and 4). The SINDA thermal analysis program solves this network.

The output is formatted to list the case and junction temperature of each component. An output file is also written for use with a plotting routine that plots contours of board surface temperature isotherms (see Fig. 5). Component temperatures are input to the reliability program and used to predict the failure rate. At this point, the PCB design/packaging engineer evaluates the reliability of his design and determines whether it meets the design requirements. If not, he can relocate some components per the isotherm data and repeat the process.

Method

The most significant feature of this effort is the AUTOMOD automatic thermal modeling program. Using this program, the actual thermal model, containing an accurate representation of all the significant thermal effects, can be created within seconds. Since one of the applications of temperature results is a reliability prediction, a proper tradeoff must be maintained between the detail necessary to achieve satisfactory accuracy and the run time and complexity of the model.

For modeling purposes, the PCB's are divided into three categories:

1) Multilayer boards that contain at least one solid copper power or ground plane (0.0028 in. thick).

2) Boards without solid copper planes (i.e., trace planes only or single-layer boards).

3) Metal core—leadless chip carrier (LCC) boards.

This paper addresses the first two types only.

In multilayer board construction, layers of copper-clad plastic sheets are alternated with layers of preimpregnated (prepreg) glass sheets that act to bond the plastic sheets into a board. The number of copper-clad layers in the board is determined by the board electrical requirements. The layers consist of trace, power, and ground planes. Trace layers contain considerably less copper than power or ground planes. Considering this, the effect of conduction through the traces is ignored.

For either case, AUTOMOD creates two layers of nodal elements. Multilayer boards are modeled with the top layer simulating the composite fiberglass material and the bottom layer simulating the solid copper planes. Lateral conduction in the board is modeled on the basis of heat flow through the solid copper power and ground planes. Conduction between the top and bottom layers is based on half the thickness of the board and uses the conductivity of G-10 fiberglass.

Single-layer boards (boards without solid copper planes) are modeled with each layer simulating one-half the board thickness. Lateral conduction takes into account both layers and uses some adjusted thermal conductivity to simulate the effects of the trace layers. Conduction between the layers also uses the adjusted conductivity value.

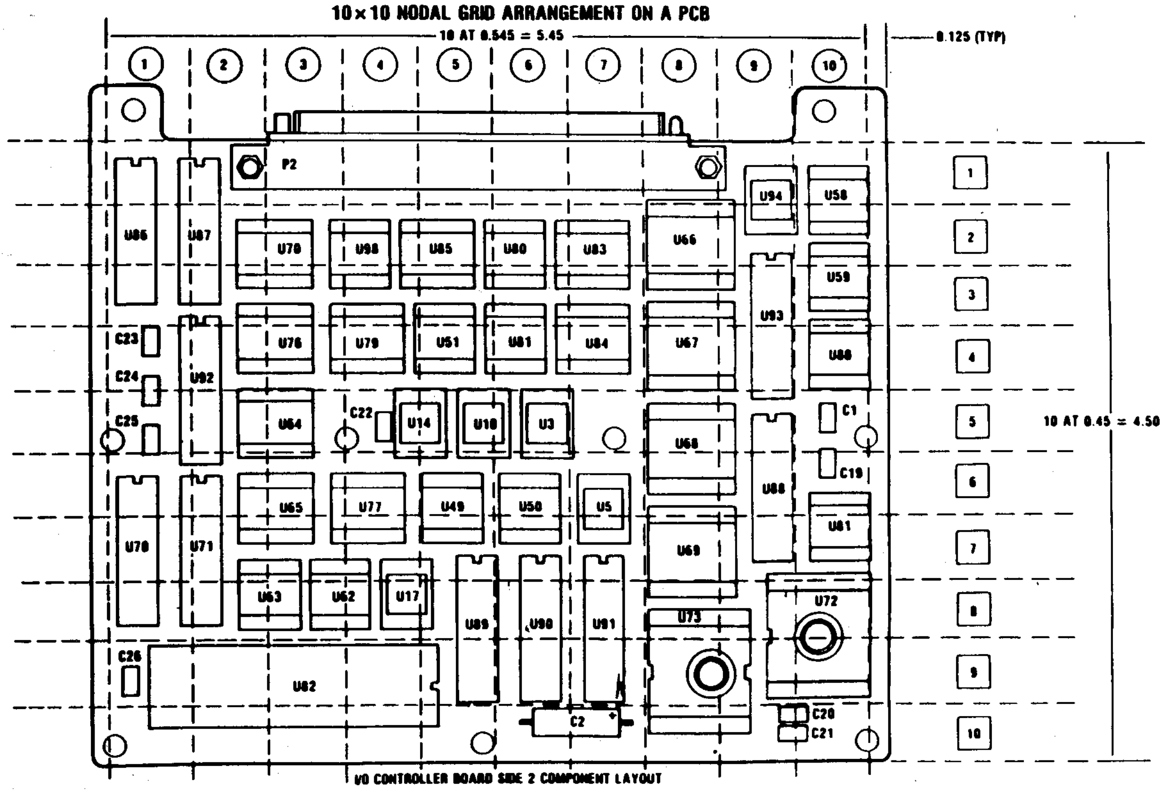
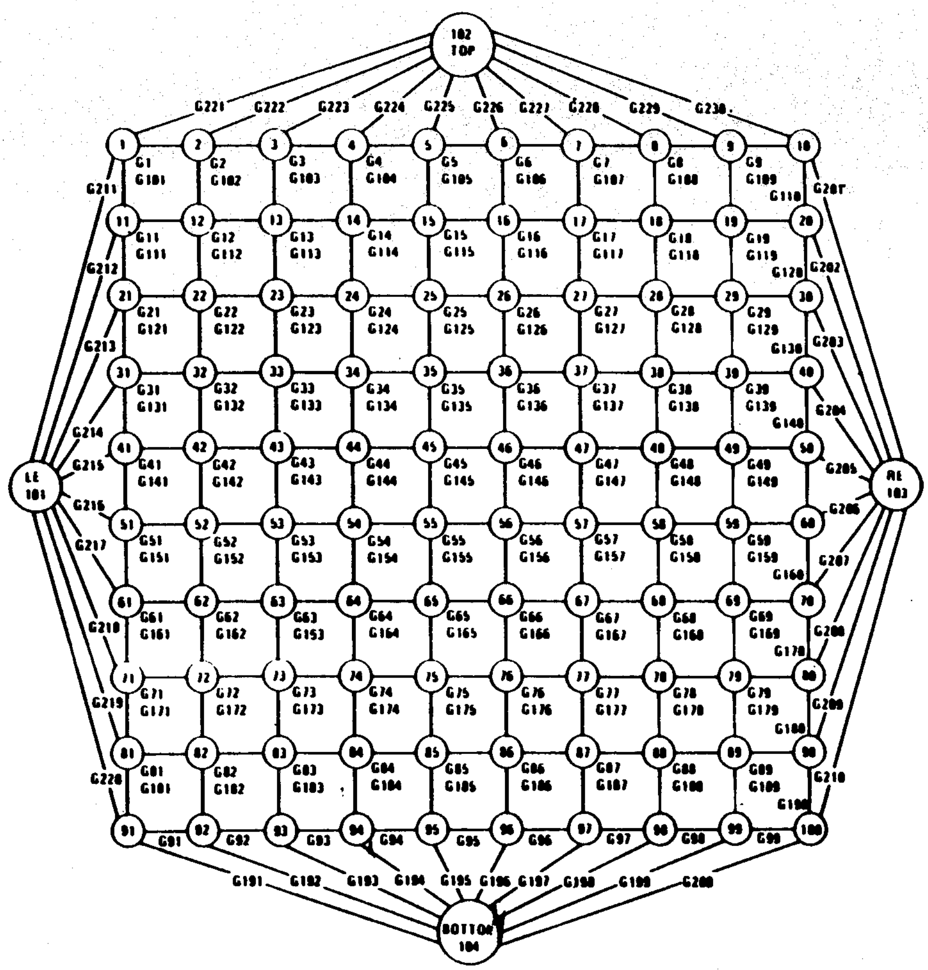


Fig. 3 Thermal mathematic model of PCB.



NODES: 1-104
CONDUCTORS: G1-G220
G1-G99 = SYM/SAME
G101-G190 = SYM/SAME
G201-G220 = SAME
G191-G200 AND G221-230 = SAME

SINDA
"100 NODE" MODEL
(AND 4 NODE BOUNDARY)

Fig. 4 10 × 10 nodal grid arrangement on a PCB.

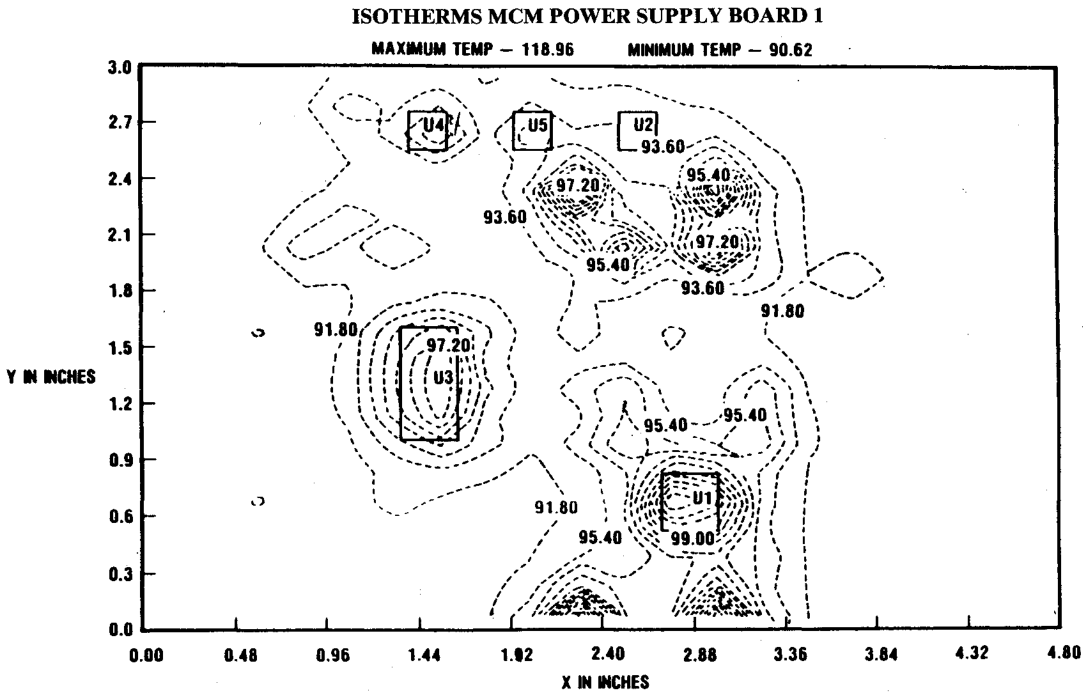


Fig. 5 Plotted board surface temperature isotherms.

In order to reduce model complexity, the individual components are not modeled as separate nodes. The thermal masses of the components are small enough to be neglected. Instead, the components are included as heat sources to the appropriate node. The amount of heat input to the board has been reduced by the amount that has been dissipated away by convection and radiation. The remaining heat is distributed through the leads to the bottom layer and through direct contact to the top layer. If the component does not directly contact the board, conduction across the air gap is used.

Free convection and radiation heat transfer from the surface of the PCB is treated identically for both types of boards, although these effects are more significant for boards without solid copper planes to spread the heat. AUTOMOD uses considerable detail to accurately model free convection and radiation. An equivalent heat-transfer coefficient is defined in Eqs. (1) and (2), where h_c is the free convection coefficient, h_r the radiation coefficient, and h_{env} the total or environmental coefficient.

$$q = h_{env} A(\Delta t) \tag{1}$$

$$h_{env} = h_c + h_r \tag{2}$$

Localized high-temperature areas will produce higher heat-transfer coefficients than areas with little or no heat input. The heat-transfer computations begin with user-specified heat-transfer coefficients. Typical values are $h_c = 1.2$ Btu/h-ft^2-°F (6.8 W/m^2-°C) and $h_r = 1.5$ Btu/h-ft^2-°F (8.5 W/m^2-°C) for a 10°F (5.6°C) temperature difference and 150°F (83.3°C) environmental temperature. A separate h_{env} is calculated for each nodal element prior to each iteration. Equation (3) is used to calculate h_c, where the value of C is 0.54 for a horizontal flat plate, Δt is the temperature difference between the nodal element (from the previous iteration) and the environment (in °F), and L is the characteristic length (in ft) from Eq. (4).[1]

$$h_c = 0.52C(\Delta t/L)^{0.25} \tag{3}$$

$$L = 2\ (\text{length} \times \text{width})/\text{length} + \text{width} \tag{4}$$

Equation (5) is used to calculate the radiation coefficient, where ϵ is the emittance and T_{av} the average temperature of the environment (in °R).[2] This is an equivalent coefficient, which takes into account the temperature difference to the fourth power, the Stefan-Boltzmann constant, and a view factor of 1.0 to the environment.

$$h_r = 0.00685\epsilon(T_{av}/100)^3 \tag{5}$$

AUTOMOD also provides the option to account for board support mounts, called "bosses," used to bolt the PCB securely in place and protect against vibration failure. These bosses act as local heat sinks and significantly affect the temperature of the board.

Once SINDA completes the board temperature calculations, they are used to determine the temperature of the component cases and junctions. The junction temperatures are used in the reliability predictions.

Results and Conclusion

Several existing printed circuit boards (PCB's) have been analyzed using this automated analysis procedure. The results have been compared to conventional analysis methods and indicate a close correlation. The next step in the development of this process is thermal testing of PCB's. The test results will be used to fine-tune the thermal model that AUTOMOD constructs.

Once the C-CARD process is fully developed and implemented, it will provide the electronics packaging engineer with a tool for quickly and interactively assessing the temperature and thermal-driven reliability of electronic equipment during the early circuit board layout and packaging phases of the design.

References

[1] Steinberg, D.S., *Cooling Techniques for Electronic Equipment,* Wiley, New York, 1980.

[2] *Marks' Standard Handbook for Mechanical Engineers, Heat,* 8th ed., edited by T. Baumeister, McGraw-Hill, New York, 1978, pp. 4-69.