20. M. S. Mock, "On the convergence of Gummel's numerical algorithm," Solid-State Electron., 15, 1-4 (1972).
21. I. I. Abramov and S. G. Mulyarchik, "Method of vector relaxation of systems in problems of multidimensional numerical analysis of semiconducting devices," Izv. Vyssh. Uchebn. Zaved., Radioelektron., 24, No. 6, 59-67 (1981).
22. A. A. Samarskii, Theory of Difference Schemes [in Russian], Nauka, Moscow (1977).
23. A. A. Samarskii and E. S. Nikolaev, Methods of Solving Grid Equations [in Russian], Nauka, Moscow (1978).
24. I. I. Abramov, "Algorithms of numerical analysis of bipolar semiconducting devices and their comparison," in: Proc. Conf.: Problems of Using Contemporary Radiophysical Methods to Enhance the Effectiveness of Production and Automation of Scientific Studies [in Russian], Pt. 2, Minsk (1981).

A SYSTEM FOR COMPUTER-AIDED THERMAL DESIGN

G. N. Dul'nev and B. V. Pol'shchikov

UDC 536.24:681.2

A systems approach and design unification are used in a method of automating the thermal design of electronic devices.

The design of a device may involve electrical, mechanical, optical, and other systems, and many specification have to be met: functional, technological, working, reliability, economic, etc. These requirements can be optimally met by means of two major principles used in computer-aided design (CAD) systems: design standardization and a systems approach. The devices may be based on a modular principle, which involves a hierarchic tree, i.e., a device is divided into several units, which themselves are divided into units of lower rank. Therefore, the structure is to be considered as components that are largely standardized and have a hierarchic relation (electronic components, cassettes, boards, blocks, cooling system, etc.).

In a systems approach to design, the individual sections or devices are considered as a whole; characteristic units are identified together with the links between them, as well as the effects of changes in individual components on device operation; optimum design is applied to the architecture, followed by stepwise optimization of the various units.

It must be emphasized that any deviation from integrity in the approach, with a desire to work out certain design problems to completion, while the others are left aside and considered only if necessary, will result in violation of the information links between the subsystems, which subsequently will require much time in correcting and finishing the device.

Design automation involves a set of linked problems [1], one of which is the computer-aided thermal design (CATD) system, which is a subsystem in the general computer-aided design (CAD) system. The CATD includes ways of simulating the temperature distributions in complicated devices, methods of automating the thermal calculation for various working conditions, and computer organization of the thermal-design system.

The thermal design is closely related to other subsystems and is realized at various stages: in simulating the functions, in defining the components, in locating them, and in providing the technology.

At the simulation stage, one analyzes the circuit and identifies the overloaded points by considering the heat produced for each component.

In selecting the components [2] from a given logical description of the system as a whole, a hierarchic structure must be set up such that any subsystem in the first level is contained in a rack, section, panel, etc. of given size. Then the units of the second rank (cassettes and blocks) and those in the third rank (boards containing micromodules, integrated circuits,

---

Leningrad Fine Mechanics and Optics Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 44, No. 2, pp. 293-298, February, 1983. Original article submitted October 28, 1981.

 0022-0841/83/4402-0206$07.50

and LSI) are used as major components of the subsystems at the first and second levels etc. The basic units in the last level (for example, the third) must be standard sets of interchangeable units (microcircuits, integrated circuits, microprocessors, semiconductor devices, relays, temperature transducers, etc.). At this stage, the thermal design consists in optimum choice of the units and components with regard to the thermal conditions.

The location [2] consists in defining the positions of the modules, units, and other parts of the electronic and electrical equipment, including the component topology. At this stage one considers not only the installation and connection requirements but also the features of the thermal conditions. In certain cases, location as such may be absent, as for example in designating optical devices, thermostats, and refrigerators. Here the location is determined by the functions.

However, the main part of the thermal design is performed at the stage where the construction is defined together with the cooling system. To realize SATD, it is necessary to classify constructions on various parameters, working conditions, purpose, economy, and other features, and it is also necessary to standardize the components and determine the characteristics and parameters of these, while also developing the system for automated thermal calculation [3] and defining the basic principles of computer-aided design for them, which involves formalizing various processes in the design and setting up a data bank and an information retrieval system, which utilizes an interactive or some other design system, which requires a technical-support system to the CAD.

Some of these tasks are considered below.

Device and Component Classification. This is governed by various factors. The design of standardized instruments or novel devices involves the initial definition of basic designs or the use of analogs to the future device. The choice of basic design is determined by the purpose, the working conditions, the form of production, and other specifications. The designer must have a reasonably complete conception of the class of devices in order to define an analog, i.e., he must possess ordered information (a classification table) for the designs and the changes required in accordance with economic requirements. The classification should cover all the commoner designs, since various forms of device with detailed specifications for purpose, working conditions, and so on may be based on any analog. Also, each basic design must have an analogous classification (ordered information) on the components.

Basic Principles for the General Logical Design Sequence. These amount mainly to the following: automatic selection of device architecture followed by stepwise optimization in the individual units; design by levels in the hierarchy, with the stages linked together by successive approximation; division of the design problem into a series of formalized elementary operations capable of being effected automatically; construction of a logical block diagram for the sequence of elementary operations in the design; reduction of the design operations to linear and nonlinear programming, optimum device location, the definition of optimum units, etc.; definition of the necessary thermophysical parameters (thermal conductances, resistances, thermal conductivities, etc.) and use of these as keys to the design or development of a unit with the necessary properties; an automated search for optimum design parameters for the cooling systems (CS) together with calculation of the temperature distributions in the devices at all levels, and computer-aided design considered as a multistage iterative process for the individual elementary operations (thermal calculation, optimization, location, automatic design selection, etc.). Each process terminates with output to the terminal equipment (for example, VDU), analysis, and decision.

Design Methods for Constructions and Cooling Systems. First of all, one defines the architecture (i.e., the general scheme), the technical specification, and the specifications for the design and the cooling systems at each level. Then detailed development is performed for all levels, which are matched to one another. The block diagram (Fig. 1) illustrates the general design method, including the CS. The initial data are contained in the technical specification and include the working conditions for the devices and components, the working conditions and the external energy inputs, the permissible component temperatures, the constraints on the technical characteristics of the cooling and thermostatic systems, and the reliability, mass, volume, etc.

The initial stage is to define the structural diagram (basic design) and choose the CS, i.e., the architecture for the entire design and the individual units, along with the definition of thermal criteria for the subsequent levels. The software for this stage is provided by a specialized information retrieval system (IRS) for the basic constructions, units, components, and other parts, along with thermal models and thermal parameters (system A, Fig. 1). Information is available on the components (IC, LSI, microprocessors, micromodules, boards, transducers, regulators, etc.) and on the typical designs for the various units (panels, subblocks, instrument racks, sections, etc.), as well as on the designs of the connecting units etc. Also, the information system should provide data on the thermal and other economic characteristics of the cooling components (heat exchangers, pumps, fans, miniature refrigerators, etc.) as well as information on the methods of thermal simulation. This system should provide rapid selection, which requires that the information should be appropriately classified and represented in the computer. Usually, all the information for the technical design is contained in common information files (which are stored in the peripheral memory), where they are represented in compressed form, while the working files contain the information in expanded form.

When the architecture has been defined, the second stage begins, in which the working software suite is generated. The software (system B) for this stage consists of a library of analysis and optimization programs. In the third stage, detailed designing is performed (Fig. 1, operations 3.1, 2, 3, ...).

The design is performed in sequence according to the hierarchy in the basic analog beginning with the highest level and consists in defining the construction for the previous level at each successive stage. Here one uses data and software in systems A and B as shown in the block diagram.

Primarily (operation 3.1) one calculates the optimum geometrical, thermophysical, and other parameters of the CS (parameters of the heated zone, thermal sinks, contact thermal resistances between components, rates of general and local cooling, etc.) for level i. The latter is sometimes called installation space i.

The design problems at this stage are handled by algorithms and programs for analyzing the temperature distributions and software for choosing the optimum parameters.

The next operation 3.2 is the choice of components in terms of effective parameters for installation space i, with correction and refinement of these parameters. The election is made from the data base (i.e., from the classification table of information system A) by reference to the effective parameters found previously (operation 3.1). Usually, it is not possible to select exactly the components with the necessary thermophysical parameters, and therefore it is necessary to modify the thermal calculation. If there is no such unit or component, detailed recommendations are made on ways of realizing a suitable component (such as the use of heat sinks, thermal tubes, thermal syphons, thermoelectric cooling, etc.). In this situation it is necessary to design a new component base with the corresponding software.

The operation in the next stage 3.3 is location. The location problems are very varied because of the many possible designs. They can be divided into location in specified positions and in a continuous mounting plane. In both cases, the location may be performed in three-dimensional, two-dimensional, or one-dimensional space. Various algorithms are used, whose choice is dependent on the particular problem. In stages 3.4 and 3.5, the design is further developed using the characteristics found in 3.1 to select the cooling method and to devise the optimum structural scheme and calculate the effective parameters, i.e., one determines the necessary characteristics of the heat exchangers, fans, refrigerators, etc. Then in operation 3.5 one either selects the necessary components from the data base and modifies the thermal calculations or proposes ways of devising CS structural diagrams and develops components.

The software here is provided by the information system with its data on the organization of various CS, units, types of heat exchanger, necessary additional equipment, etc. The cycle of operations with the database is as follows. When the optimum design parameters have been selected for the CS, the heat exchanger, and so on (operations 3.1 and 3.4), the entire design along with the heat-exchange equipment is considered as a single set N, which can be split up into a series of nonintersecting and intersecting subsets combining all the standard equipment made in a given industry on the following features: power handled, reliability, weight and size parameters, method of heat removal, heat carrier, amount of additional equipment, preferred areas of use, etc.

The required form of equipment is selected in accordance with the characteristic features, e.g., the form of CS or heat exchanger. The desired construction N_{opt} is considered as an

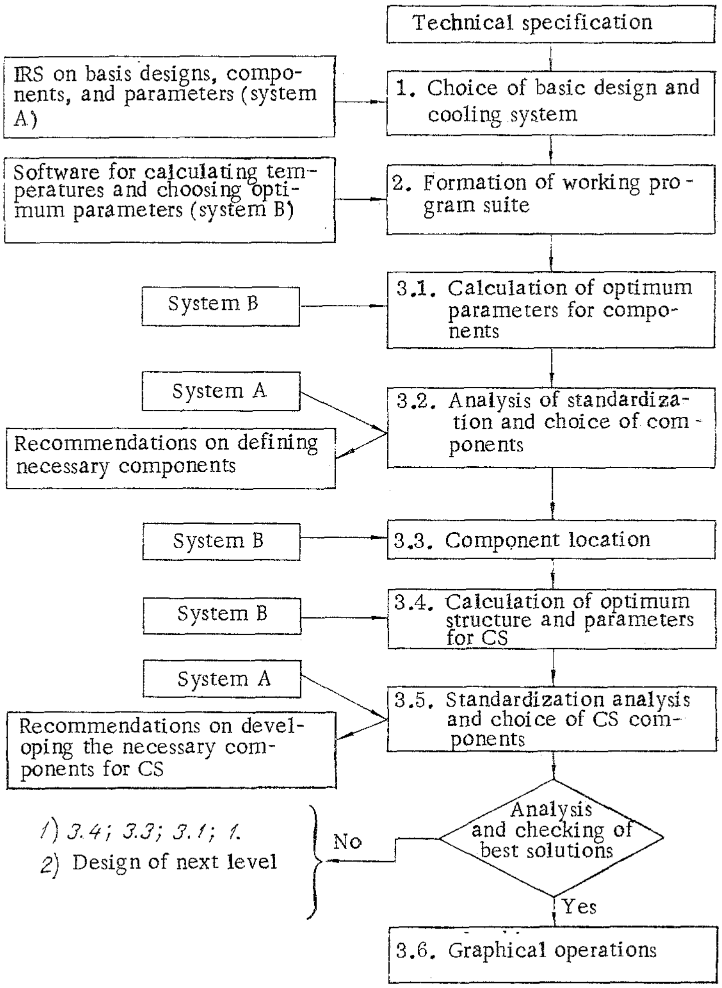

Fig. 1. Block diagram of the stage sequence in designing an instrument cooling system.

element in the set $N_{opt} \in \tilde{N}$, where $\tilde{N}$ is the entire solution region. If this region contains several elements, i.e., corresponds to several designs, then the optimum cooling is selected by considering each in relation to the price list.

When the system and form of the cooling have been established the parameters are calculated (dimensions, revised design, coolant flow rate, etc.), and then the necessary additional components are selected (fans, pumps, etc.).

The optimum selection at other stages is performed in a similar fashion.

The block diagram shows that all the design stages are iterative. If the design satisfies the technical specifications after stage 3.5, we proceed to design the next level. If this is not so, we return for correction to points 3.4, 3.3, 3.1, and 1 correspondingly. When the design of all levels is completed and the general technical specifications have been satisfied, one performs the graphical operations.

This method has been evaluated completely or partially in the design of various devices: power semiconductor converters for various purposes with natural and forced cooling, cassette electronic units, racks of electronic apparatus, printed-circuit boards, thermostatic devices, connections with a given thermal resistance, group radiators, etc.

The design method has been simplified for some of these examples, since some of the operations in the third stage can be omitted, but the general strategy and the sequence of operations remain unchanged, as do the formalized operations and other aspects.

LITERATURE CITED

1. G. N. Dul'nev and B. V. Pol'shchikov, "Heat-transfer problems in electronic equipment," Radiotekhnika, 32, No. 11, 86-96 (1977).

2. L. V. Abraitis, R. I. Sheinauskas, and V. A. Zhilevichyus, Computer-Aided Design [in Russian], Sov. Radio, Moscow (1978).
3. G. N. Dul'nev, B. V. Pol'shchikov, and A. Yu. Potyagailo, "A hierarchic-simulation algorithm for heat transfer in complicated electronic equipment," Radiotekhnika, 34, No. 11, 49-54 (1979).

A MODEL FOR FAILURE IN THE CONTACT SYSTEM OF A SEMICONDUCTOR DEVICE ON TEMPERATURE CYCLING

L. V. Bereza, A. A. Dolgov, V. G. Doroshenko,
V. M. Evdokimov, A. I. Elizarova, M. B. Zaks,
and Yu. V. Skokov

UDC 621.382.019.3:538.248

A physical model is proposed for the failure in a multilayer contact system for a semiconductor device on temperature cycling.

The following expression [1] is a formal definition of the thermal-expansion coefficient of a structure formed of plane-parallel layers with different thermal, mechanical, and geometrical characteristics:

$$\alpha = \left(\sum_{i=1}^{n} \alpha_i \overline{E}_i \bar{z}_i\right) \Big/ \left(\sum_{i=1}^{n} \overline{E}_i \bar{z}_i\right). \tag{1}$$

Then the elastic modulus averaged over a layer $\overline{E}_i$ may differ substantially from the value of Young's modulus $E_{0,i}$ (e.g., for a platy material) because the usual definition for the elastic modulus

$$\overline{E}_i = \overline{\sigma_i}/\overline{\varepsilon_i} \tag{2}$$

takes the following form in the case of an idealized loading curve for material i:

$$\overline{E}_i = \begin{cases} E_{0,i}, & |\bar{\varepsilon}_i| \leqslant \varepsilon_{0,i}; & (3.1) \\ \overline{\sigma_i}/\bar{\varepsilon}_i, & \varepsilon_{0,i} < |\bar{\varepsilon}_i| < \varepsilon_{i,\,\mathrm{cr}}, & (3.2) \\ 0, & |\bar{\varepsilon}_i| \geqslant \varepsilon_{i,\,\mathrm{cr}}, & (3.3) \end{cases}$$

and the value of the equivalent layer thickness $\bar{z}_i$ in (1) for an unchanged geometrical thickness z_i is defined by the thermal-stress distribution in the layer

$$\bar{z}_i = \frac{1}{\sigma_i} \int_i \sigma_i dz_i \tag{4}$$

and can be established by methods from the theory of material resistance.

One can examine the thermal stresses in a multilayer contact system that includes a layer of metal of thickness about 1 μm deposited on a semiconductor (for example, silicon) of thickness $\geqslant$100 μm (Fig. 1), and it can be shown that there is substantial plastic strain in the metal zones in contact with the semiconductor when the temperature changes by only a few tens of degrees. The curve for temperature cycling of the metal then takes a hysteresis form (1), and the area of the loop is assumed proportional to the specific energy dissipated, which initiates the formation of reversible defects in the metal lattice. A defect is formed in the latter at the stage of plastic stretching when the system cools, and vanishes (at least partially) on subsequent temperature rise.

The semiconductor in contact with the layer of plastically deformed metal is subject to tensile stresses on heating (and the magnitude of these may be at the critical level for the semiconductor at the points of localization of the defects in the metal), and it senses the defect, and transforms it by virtue of its brittleness into an irreversible one.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 44, No. 2, pp. 298-304, February, 1983. Original article submitted November 16, 1981.

 0022-0841/83/4402-0210$07.50