Thermal modeling of the infrared reflow process for Solder Ball Connect (SBC)

by H. V. Mahaney

A thermal model of the infrared reflow process has been developed for an FR-4 card populated with an array of Solder Ball Connect (SBC) modules. The analysis of the three-dimensional, transient, finite element model accounts for radiative exchange within the infrared oven and for the heat conduction (nonisotropic) within the modules and card. Transient temperature profiles of selected points and three-dimensional temperature distributions at selected times are presented to describe the primary heat-transport mechanisms. Numerical predictions and empirical data indicate that the SBC modules are relatively isothermal throughout the infrared reflow process. Therefore, every solder ball within the array exhibits a nearly identical thermal profile. This result is fortunate, since the inner solder ball connections cannot be visually inspected. The influence of module spacing and the ability to improve the reflow process by use of a high-emissivity cap coating are demonstrated.

Introduction

Solder Ball Connect (SBC) is an area array surface mount technology (SMT) in which a ceramic substrate containing one or more chips (a "module") is connected to an FR-4 card by the use of an array of high-temperature-melting 90%Pb/10%Sn solder balls and eutectic solder [1]. Interconnection between the card and the SBC module (as well as other surface mount components, in general) is typically accomplished with an infrared (IR) reflow process. In this process, a printed circuit card with solder paste applied to its pads and with modules placed thereon is passed through an infrared reflow oven. The primary purpose of this reflow process is to melt the solder paste, wet the surfaces to be connected, and solidify the solder into a strong metallurgical bond [2]. The reliability of this bond is inherently dependent upon the thermal profile the bond experiences throughout the IR reflow process.

A radiation-dominated IR reflow oven is shown schematically in **Figure 1**. Since the oven is nearly 100 times as long as the spacing between the top and bottom heater panels, Figure 1 is not drawn to scale. A conveyor belt, moving at constant velocity, is employed to transport the card populated with modules through the oven. Forty

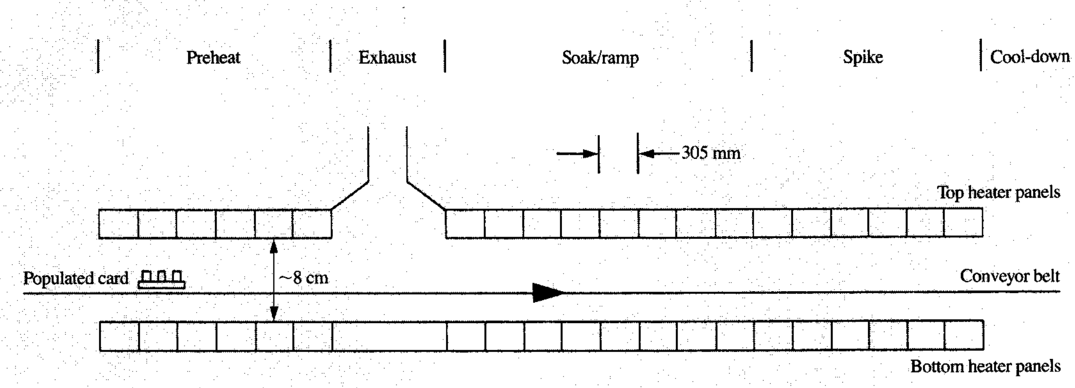


Figure 1

Schematic of infrared reflow oven.

heater panels, half above and half below the conveyor belt, are individually set to specified temperatures and used to heat the card and modules. These heater panels employ the secondary-emission principle, in which an imbedded resistive element heats a flat surface which in turn is the radiant source [3].

A typical oven profile consists of an initial preheating region, an exhaust section, a long soak/ramp region, and a final spike region. The initial preheat region provides a period of rapid heating that allows fast processing without overstressing components. To remove the paste volatiles from the system, air is drawn into the oven from both ends and is forced out of the system via the exhaust stack. The soak/ramp region is characterized by slower heating, allowing the temperature differentials within the assembly, which are created by the preheat section, to decrease, and bringing the entire assembly to a more or less uniform temperature just below the eutectic temperature. In the spike region, the temperature of the solder is raised above the eutectic solder reflow temperature (183°C) for 30 to 60 seconds, in order that the solder completely wet the solder joint.

Previous thermal modeling of the IR reflow process is limited to a few studies. Glaser and Juaire [4] performed a two-dimensional finite element thermal-conduction analysis of a representative cross section of a typical plastic leaded chip carrier undergoing an IR reflow process. However, time-dependent data from experimental measurements were used to define the thermal boundary conditions in the model; therefore, the radiative and convective transport within the oven was not directly simulated. Guided by the work of Fernandes et al. [5], Eftychiou et al. [6] employed a hierarchical modeling approach to estimate the thermal response of a card assembly undergoing an IR reflow process. In the latter study, a "tunnel model" that employed convective correlations was used to estimate thermal conditions within the oven, while a "card model" used the predictions of the tunnel model, in conjunction with a conductive and radiative heat transfer analysis, to estimate the detailed thermal response of the card. This two-dimensional analysis was applied to a series of J-leaded, plastic-encapsulated chip carriers mounted on an FR-4 circuit card that was processed in a relatively short oven of length 720 mm. Extensions of this model, which include the solution of the two-dimensional Navier–Stokes and energy equations, are given in [7] and [8]; they were applied, respectively, to an unpopulated card and a card populated with plastic-encapsulated surface mount modules. In both cases, the same short oven length (720 mm) was used. In these simulations [6–8], the thermal response of the card was shown to be radiation-dominated, while convective heating of the card occurred early in the reflow process and convective cooling occurred near the end of the process. Overall variations in the predicted solder temperature profile due to changes in convective heat transfer were modest, but the period during which the solder was molten was sensitive to the convective transport.

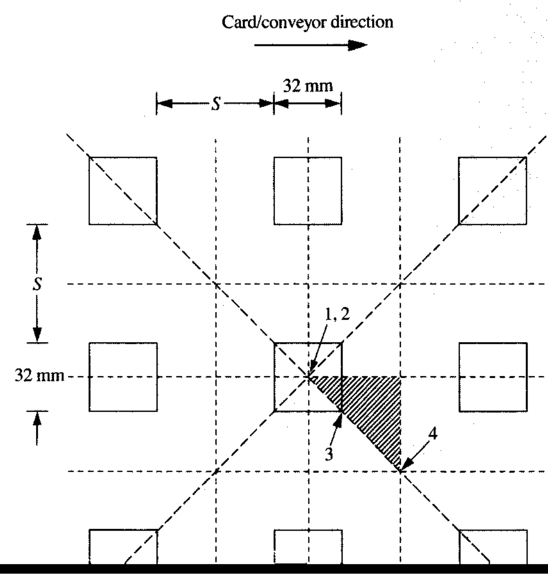
On the basis of the work cited above, which neglects convective transport within the oven, this paper discusses a thermal analysis of the IR reflow process for SBC modules being processed within an industrial-size furnace of length 7010 mm. The construction of the SBC assembly, however, is significantly different from that of the plastic-encapsulated chips considered above [4, 6, 8] in terms of module-to-card interconnection, dimensions, and thermal properties (e.g., density, specific heat, thermal conductivity, and emissivity).

Numerical model

A thermal conduction analysis, with imposed radiative boundary conditions, was performed using the general-purpose finite element programs CAEDS® [9] and ANSYS® [10] to simulate the IR reflow process for SBC. Both radiative and convective boundary conditions were applied in the subsequent cool-down process. The three-dimensional, transient, nonisotropic heat-conduction equation solved in this analysis may be expressed as

$$\rho c_p\left(\frac{\partial T}{\partial t}\right) = \frac{\partial}{\partial x}\left(k_{xx}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{yy}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{zz}\frac{\partial T}{\partial z}\right) + q.$$

(The symbols are defined in the Appendix.) This equation is solved by an implicit direct integration scheme based on a modified Houbolt method employing a quadratic temperature function [10].



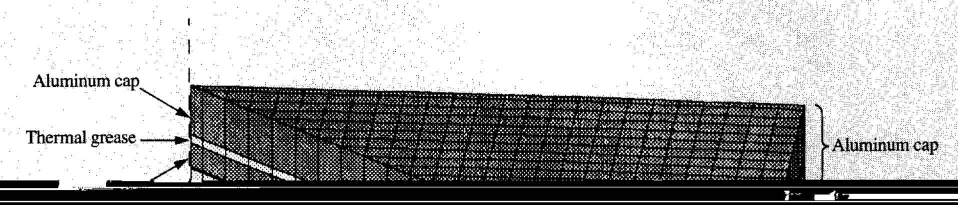

Aluminum cap
Thermal grease
Aluminum cap

Table 1 Thermophysical properties of materials used in model.

Material	*Density* ρ (kg/m^3)	*Specific heat* c_p (J/kgK)	*Thermal conductivity* k_{xx} *and* k_{yy} (W/mK)	*Thermal conductivity* k_{zz} (W/mK)
FR-4 and power planes	1800	1570	27.2	0.215
FR-4 and vias	1800	1570	22.3	25.6
Solder ball	10500	167	48.6	48.6
Ceramic substrate	3800	780	*	*
Epoxy bond	1230	1900	0.5	0.5
C-4/air layer	1380	200	4.7	4.7
Chip	2330	*	*	*
Thermal grease	3250	730	1.15	1.15
Air	0.77	1021	0.037	0.037
Aluminum cap	2702	*	200	200

*See Table 2.

Table 2 Temperature-dependent properties of materials used in model.

Material	*Property*	*25°C*	*125°C*	*225°C*	*325°C*
Ceramic substrate	Thermal conductivity k_{xx}, k_{yy}, k_{zz} (W/mK)	17.6	11.6	11.6	11.6
Chip	Thermal conductivity k_{xx}, k_{yy}, k_{zz} (W/mK)	148	98.9	80.4	61.9
Chip	Specific heat c_p (J/kgK)	712	790	829	867
Aluminum cap	Specific heat c_p (J/kgK)	903	949	991	1033

element that participates in the radiative exchange. With a second approach, the card may be assumed to participate in radiative exchange with a single pair of heater panels whose temperatures are linearly ramped from time step to time step, depending upon the position of the card with respect to the heater panels. The latter technique has the advantages that since the view factors are independent of time, they need be calculated only once, and that the number of radiative links needed for the analysis is one third of that required for the former approach, thus significantly decreasing the CPU time required for the solution. This latter option was employed, and the time step, t_s, was set to one third of the time necessary for a module to travel the length of a heater panel: $t_s = L_p/3V$, where L_p is the heater panel length and V is the constant conveyor belt velocity. As a result of this ramping process, the oven panel temperature employed in the simulation is linearly ramped from $T_{\text{panel},\,n}$, the temperature of heater panel n, to $T_{\text{panel},\,n+1}$, the temperature of heater panel $n + 1$, in three steps and simulates the smooth transition from one heater panel to the next.

Thermal transport within the exhaust region of the oven is modeled by assuming that the radiative exchange occurs between the populated card and the exhaust flue (which is at 150°C because of convective heat transfer with the exhaust air).

The radiation model assumes diffuse gray behavior*; therefore, the net radiative transfer between the reflow environment (i.e., heater panels, exhaust, and surroundings) and each surface element of the model that participates in the radiative exchange may be expressed as

$$Q = \sigma\varepsilon FA(T_{\text{env}}^4 - T^4),$$

where Q is the heat flow rate; σ is the Stefan–Boltzmann constant; ε is the emissivity; F is the view factor; A is the exposed surface area of the finite element; T is its surface temperature; and, as shown in **Figure 4**, T_{env} is the temperature of the reflow environment, which comprises the oven (heater panels and exhaust) and the surroundings associated with the cool-down process. In this study, the top and bottom heater panels at each location were set to the same temperature.

Emissivity values used in the analysis are given in **Table 3**. The emissivity values for the FR-4 card and aluminum cap were measured using an infrared radiometric microscope. The emissivity of the aluminum cap was found to be sensitive to the surface finish/oxidization and to decrease with increasing temperature; the emissivity employed

*A gray surface is one for which the spectral emissivity and absorptivity are independent of wavelength over the spectral regions of the surface irradiation and emission. A diffuse surface is one for which the intensity associated with the incident, reflected, and emitted radiation is independent of direction.

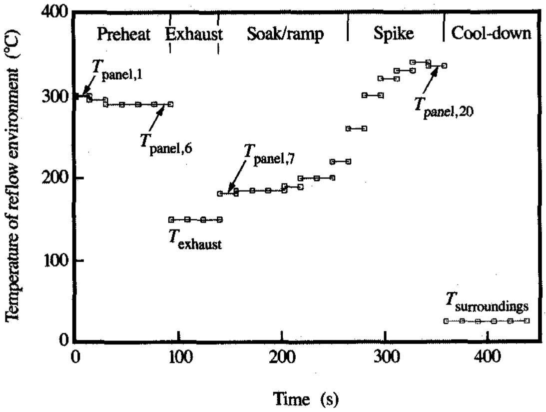


Figure 4

Temperature of the reflow environment, which comprises heater panels, exhaust, and surroundings.

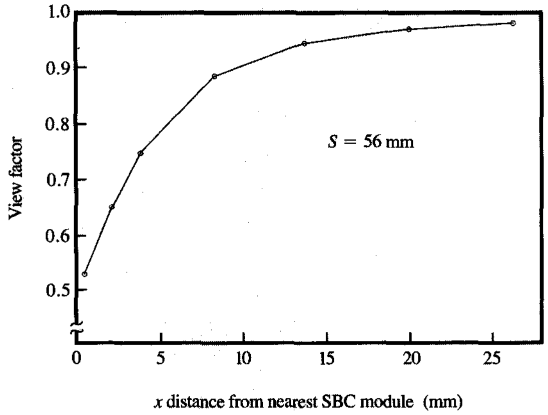


Figure 5

View factor for the top surface of the card as a function of the x distance from the nearest SBC module.

Table 3 Emissivity values used in model.

Material	ε
[redacted]	

module spacing = 56 mm) as a function of the x distance from the nearest SBC module. As the distance from the SBC module increases, the effect of shading diminishes, so [redacted]

Experimental methods

An FR-4 card populated with an array of 32-mm-square SBC modules with a module-to-module spacing S of approximately 56 mm was instrumented with four type-K thermocouples. These were attached with epoxy to 1) the center, top surface of the aluminum cap, 2) the center solder ball of the array, 3) one of the four corner solder balls of the array, and 4) a point on the card that is equidistant from the center of the module and the center of the diagonally located adjacent module. The x–y locations of these thermocouples are shown in Figure 2. Transient temperature data were measured and stored using a Multichannel Occurrent Logger Evaluator (Electronic Controls Design). We estimated uncertainty associated with the temperature measurements to be 1°C.

Results

Experimental measurements of the temperature response of a populated card that moved through the IR oven at a speed of 1.95 cm/s (46 in./min) are shown in **Figure 6.** Because of the low thermal mass per unit area of the card, as well as its high emissivity, the card far from the module (point 4 in Figure 2) heats up significantly faster than does the module, in the preheat section of the oven. In the exhaust and soak/ramp regions, the temperature differential between the card and module decreases, because of the lower exhaust and heater panel temperatures (Figure 4) and because of the conduction of heat from the card to the module. In the spike region, the card far from the module again heats up significantly faster than the module. Although the temperature of the card is higher than that of the module at the beginning of the cool-down region, the thermal energy per unit area of the card is significantly less than that of the module. Because of this and the high emissivity of the card, the card initially experiences a much steeper cooling curve than the module, so that shortly after cool-down begins, a temperature inversion is expected in which the card far from the module will be cooler than the module, and heat flow via conduction will proceed from the module to the card.

During the IR reflow process, temperature differentials within the SBC modules are small. The temperature response of the center of the top surface of the aluminum cap is seen to be nearly identical (within 5°C) to that of the center solder ball directly beneath the cap measurement point. Since a small but finite time is required for the heat to be conducted from the edge of the module to the center, the corner solder ball heats up slightly before the center

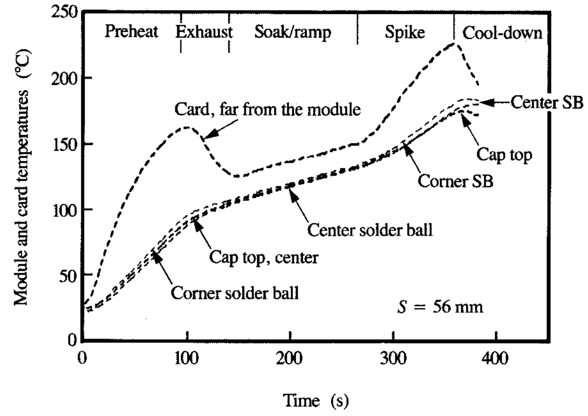


Figure 6

Measured temperature profile for a card with 32-mm-square SBC modules and a module-to-module spacing of 56 mm.

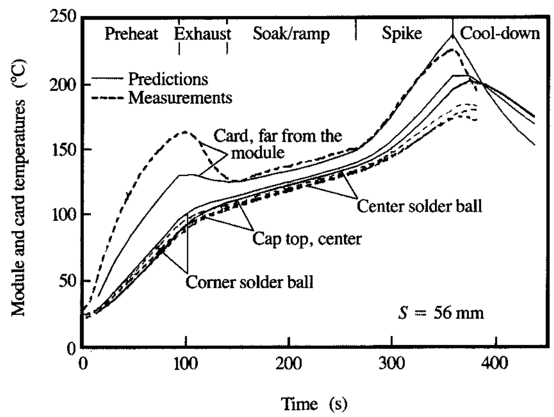


Figure 7

Comparison of measured and numerically predicted temperature profiles for a card with 32-mm-square SBC modules and a module-to-module spacing of 56 mm.

maximum temperature experienced are nearly the same for

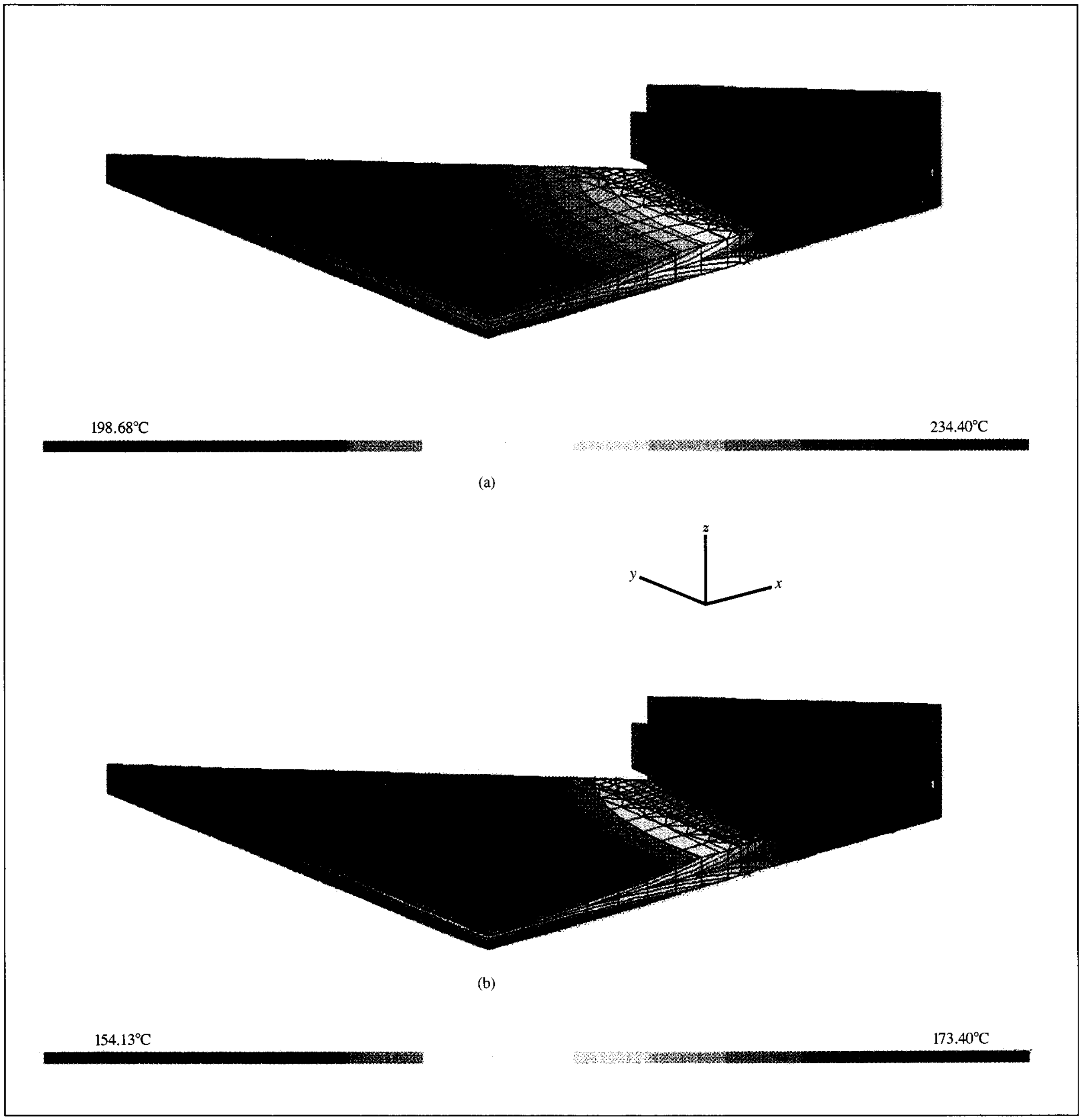
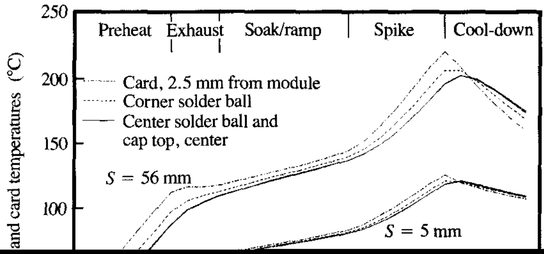


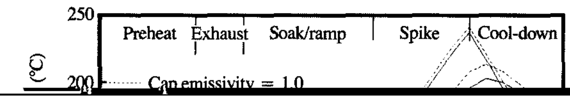
Figure 8

Three-dimensional temperature distribution for card and SBC module when the module is (a) at the end of the spike region (t = 360 s) and (b) at the end of the cool-down simulation (t = 438 s). For plot (a), the temperature differential between neighboring isotherms is 3.25°C; for plot (b), it is 1.75°C.

thermal profiles. This is because the absence of visible failures among the solder ball connections on the periphery provides some confidence that the remaining solder ball connections are satisfactory.

In **Figure 7**, numerical predictions for this IR reflow process are compared with the experimental results of Figure 6. Numerical predictions of the temperature of the card surface far from the module are significantly lower than the measured temperatures in the preheat and exhaust sections, but are in excellent agreement during the soak/ramp, spike, and cool-down regions (within 12°C). Numerical predictions for all measured positions on the module are in excellent agreement with the measured data in the preheat, exhaust, and soak/ramp regions (within 6°C), but exceed the measured temperatures in the spike region. This discrepancy is attributed to convective cooling within the oven due to the inflow of unheated air at the oven exit, which is not included in the current analysis. The following trends described above for the experimental data are also evident in the numerical predictions: a) the widening temperature difference between the card far from the SBC module and the module itself in the preheat and





11. The maximum temperature of the card occurs at the end of the spike region. For a cap emissivity of 0.2, the card temperature exceeds that of the center solder ball by up to 41°C, but this temperature difference can be reduced

Appendix: Symbols

c_p	specific heat
k	thermal conductivity
q	volumetric heat flow rate
S	module-to-module spacing
t	time
T	temperature
x, y, z	spatial coordinates
ε	emissivity
ρ	density

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