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This paper appears in: Components, Hybrids, and Manufacturing Technology, IEEE Transactions on
Publication Date: Dec 1979
Volume: 2 , Issue: 4
On page(s): 512 - 517
ISSN: 0148-6411
Current Version Published: 2003-01-06

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Experimental Investigation of Mounting Thermal Resistance of Flatpacks on Circuit Boards

THOMAS F. MOVIUS, IVAN R. JONES, AND JAMES M. KALLIS

Abstract—Thermal tests were performed on radar digital module circuit boards to measure the thermal effect of various size gaps between the circuit board and the flatpack integrated circuit (IC) case and also the thermal resistance of the circuit board. These IC's are cooled by conduction through the circuit board to an air-cooled heat exchanger. The thermal effect of the gap filled with air, and also filled with an adhesive, was measured. The temperature differences between pairs of locations on the flatpack IC case, particularly between the top and the bottom center, also were measured. These tests are described: the test results are presented, discussed, and compared with analytical predictions; and conclusions are given. The key conclusions are that the filler is quite effective in lowering the IC junction temperatures and, in fact, has a larger thermal effect than the gap size. For example, filling a 5-mil ($1.27 \times 10^{-3}$ m) gap reduces the junction temperature by $12^\circ$C, whereas reducing the gap from 5 mils ($1.27 \times 10^{-3}$ m) to 0 reduces it by only $3^\circ$C. The combined thermal resistance of the gap and the circuit board is a linear function of the gap.

INTRODUCTION

In a radar digital module, thermal effects of the gap between the integrated circuit (IC) case and the circuit board, and of the board itself, are of considerable interest because they have a significant effect on the operating temperature of the IC. Ideally, one would like to fabricate the modules so that the gap is zero, i.e., so that the IC flatpack case touches the solder pads, which act as thermal vias. Because of tolerances in forming the flatpack leads, however, a zero gap cannot be assured in production. To prevent stresses in the leads, which could cause solder cracking, the lead-forming process is specified so as to ensure that the solder joints are unstressed. As a result, gaps as large as 5 mils$^1$ can occur in production. An air layer several mils thick can have a significant thermal resistance and thus can have a significant effect on the IC junction temperature and thereby on reliability.

Methods for minimizing the gap thermal resistance include holding tight tolerances on the lead-forming dimensions, which increases the cost of the process, and filling the gaps with a material having a thermal conductivity higher than that of air. To evaluate these candidate methods, it is necessary to have quantitative data on the thermal effects of the gap and of the effectiveness of the filler.$^2$ No previous investigation of the type reported herein is known to the authors.

Manuscript received May 23, 1979; revised August 15, 1979.

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1 In this paper the gaps and other small dimensions are measured in mils ($1 \text{ mil} = 2.54 \times 10^{-6} \text{ m}$).

2 In this paper the word “filler” means an adhesive filler, rather than a filler used in adhesives and potting materials.

APPARATUS

Circuit Boards

Special circuit boards were designed and fabricated for these tests. The special thermal test printed wiring boards (PWB's) incorporated the normal radar design standards, as well as standard materials and processes, but had special simplified circuitry to maintain a fixed dc input signal to the IC's and thereby achieved a constant power dissipation. The circuit provided power to 16 IC's, each having 24 leads, which were arranged in two rows of eight each. Each board consisted of 12 circuit layers and was approximately 90 mils thick. The quantitative results reported herein may vary for different PWB configurations and for different component types.

Adhesive

Tests were performed using an IC thermal transfer adhesive. A low-viscosity adhesive formulated from low-strength epoxy resins catalyzed by an aliphatic amine was used. It is produced by Ablestik Adhesives Company, Gardena, CA, under the name Ablebond 907-1. The adhesive was applied under the flatpacks after they were soldered to the PWB. Because the adhesive was of the post-application type, it was simple to test the PWB's with unfilled air gaps, prior to application of the adhesive, for comparison with the filled-gap data.

Integrated Circuit Flatpacks

The IC's used in these tests were SN54S181W arithmetic logic units/function generators, whose dissipation was measured to be approximately 0.5 W. These IC's were selected because their dissipation was high relative to that of the other IC's in radar sets of interest. These 24-lead devices had 3/8-inch ($9.52 \times 10^{-3}$ m) by 19/32-in ($1.51 \times 10^{-2}$ m) ceramic cases.

Lead Forming

The leads of all the flatpacks were formed on adjustable tooling. Some were formed on a hand die and some on an automatic die (the prototype of a production flatpack lead former).

The definitions of the lead-forming dimensions used herein are illustrated in Fig. 1. The gap (sometimes called bondline)
is the distance between the bottom of the flatpack case and the top of the solder pads (which act as the thermal vias) after soldering. The thermal vias, which protude approximately 4 mils above the circuit board, did not completely span the area of the flatpack case; consequently, even when the gap was zero, the portions of the flatpack case under which there were no thermal vias were separated from the circuit board by a 4-mil-thick layer of air or adhesive. To achieve the objectives is the distance between the bottom of the flatpack case and soldering. The thermal vias, which protude approximately 4

Boar Assembly

Two PWB's (denoted 1013 and 4019) were employed in these tests, with 16 IC's per board. Neither board was conformally coated. The flatpacks were hand-soldered with shims inserted underneath them to preserve the intentional gap.

A nondestructive technique was developed to measure the gaps. The technique is illustrated in Fig. 1. Prior to soldering, the thickness $t$ of each flatpack case was measured at each end (the pin 1/pin 24 end and the pin 12/pin 13 end) with a micrometer, and the distance $b$ between the top of the solder pads and an arbitrary reference plane was measured under each corner (the pin 1 corner, the pin 12 corner, the pin 13 corner, and the pin 24 corner) with a dial indicator. After soldering, the distance $h$ between the top of the flatpack case and the same reference plane was measured at each corner with the dial indicator. The gap $g$ was then computed by

$$g = h - b - t.$$  \hfill (1)

This procedure yielded 4 values of $g$ for each flatpack. A single value for each flatpack was computed by disregarding the highest and lowest values and then averaging the remaining two values.

As a check on the dial-indicator measurements, selected IC locations were encapsulated with a transparent resin and microsectoned. Three sections along the IC, one near each end and one at the center, were photographed with 18-times magnification. From these photographs, nine gap measurements were made for each IC. The gaps measured by microsectioning were consistently 2-3 mils higher than those measured with the dial indicator. The gap, however, varied considerably from point to point. At several locations where the gap measurement was not recorded, the flatpack case appeared to be touching the solder pad. The conclusion of this comparison is that, in view of its important advantage of being nondestructive and in view of the relatively large variation in the gap across the flatpack, the dial-indicator technique is satisfactory for measuring gaps.

**TEST CONDITIONS AND INSTRUMENTATION**

Each thermal test PWB was bonded to a 3/8-in thick aluminum plate, which was flat to within 0.5 mil and had a G3 finish; the flatness was specified to improve the precision of the dial-indicator gap measurements. The bonding material was a standard radar adhesive. The plate was bolted to a 1/2-in thick, liquid-cooled cold plate, using a nonsilicone thermal paste in the interface. By controlling the temperature of the liquid coolant, the temperature of the aluminum plate (and hence the PWB ground-plane temperature) could be maintained at any desired temperature.

This plate temperature and the ambient air temperature were maintained at 71°C (344 K), and the pressure altitude was maintained at 70 kft (2.13 X 10^6 m). To accomplish this the tests were performed in a temperature/altitude chamber. This temperature and altitude were chosen to approximately simulate typical airplane flight conditions and to minimize heat transfer through paths other than through the PWB. To prevent convective heat transfer and thereby simulate the enclosures in which the PWB's operate in flight, the PWB was covered with several inches of fiberglass insulation, which was taped at the edges to virtually eliminate any drafts from the chamber fan on the test item.

All temperatures were measured with copper-constantan thermocouples, each of which was bonded to the test item with epoxy. To evaluate temperature differences between locations on the flatpack case and between the top and bottom of the case, several locations were monitored with thermocouples. The temperature of the top center of each flatpack was measured with a 30-AWG thermocouple. Six of the 16 flatpacks on one PWB had X-shaped grooves, 10-15 mils wide, sawed in the bottom of the case. Thermocouples (36 AWG) were mounted in the groove in the bottom center of the case and between 0.100 and 0.150 in (2.54-3.81 X 10^-3 m) from the corner or edge of the bottom of the case, as well as on the top of the PWB between the solder pads underneat 12 of the 16 flatpacks on each PWB. Thermocouples were mounted on the aluminum plate and on the liquid-cooled cold plate to measure the ground-plane temperature, i.e., the temperature of the bottom of the PWB. A thermocouple also was suspended in the chamber to measure the chamber air temperature.

**TEST RESULTS**

**Temperature Gradient Around Case**

The key result of these tests was that there is a significant temperature gradient around the flatpack case. The hottest location on the case was the bottom center. The top center, however, is the most accessible location for measuring case temperatures either by thermocouples or by infrared scanning. Therefore, a quantitative relationship between the bottom center and top center case temperatures is of interest. Such a relationship existed in the present data when the data were put in the form of a thermal resistance. \((T_{BC} - T_{TC})/P,\)
where $T_{BC} =$ bottom center case temperature, $T_{TC} =$ top center case temperature, and $P =$ IC power dissipation. The measured values of $(T_{BC} - T_{TC})/P$ were independent of the gap but dependent on whether the gap is filled or unfilled. The mean values were as follows:

$$\frac{(T_{BC} - T_{TC})}{P} = 23.2^\circ C/W \text{ (filled gaps)}$$

$$\frac{(T_{RC} - T_{TC})}{P} = 29.2^\circ C/W \text{ (unfilled gaps)}$$

The bottom edge (or corner) case temperature $T_{BE}$ was essentially equal to the top center case temperature. With the filled gaps, the maximum value of $|T_{BE} - T_{TC}|/P$ was 3.2$^\circ$C/W, and the mean value was 1.7$^\circ$C/W. With the unfilled gaps, the maximum value was 5.4$^\circ$C/W, and the mean value was 1.8$^\circ$C/W.

The IC dissipation measured in these tests was approximately 0.5 W. Therefore, the difference between the bottom center and top center case temperatures was on the order of 12$^\circ$C with the filled gaps and 15$^\circ$C with the unfilled gaps. The difference between the bottom edge (or corner) and top center case temperatures was on the order of only 1$^\circ$C with either the filled gaps or the unfilled gaps.

**Thermal Resistance of PWB**

The thermal resistance of the PWB was measured with the aforementioned thermocouples on the top of the PWB underneath the flatpack and on the isothermal cold plate.

The mean values were as follows:

$$\frac{(T_{PWB} - T_{CP})}{P} = 15.9^\circ C/W \text{ (filled gaps)}$$

$$\frac{(T_{PWB} - T_{CP})}{P} = 10.4^\circ C/W \text{ (unfilled gaps)}.$$  

The PWB thermal resistance was consistently higher with the filled gaps than with the unfilled gaps. If the heat transfer were one-dimensional (i.e., if the heat flow took place only in the direction perpendicular to the plane of the PWB), then the PWB thermal resistance would be expected to be independent of whether or not the gap is filled. The aforementioned temperature gradient around the case and its dependence on whether or not the gap was filled, along with the dependence of the PWB thermal resistance on whether or not the gap was filled, suggested that the heat transfer is three-dimensional.

Development of a three-dimensional analytical model of the flatpack heat transfer could be useful in explaining the present experimental results and predicting the behavior of untested flatpacks.

**Thermal Effects of Gap and Filler**

The thermal resistance $\theta$ is defined herein as the combined resistance of the gap and the PWB:

$$\theta = (T_{BC} - T_{CP})/P.$$  

The measured thermal resistance $\theta$ is plotted as a function of the gap $g$ in Fig. 2. As was mentioned previously, the value of $T_{BC}$ was measured directly with a thermocouple mounted on the bottom center of the case for some of the flatpacks. For the other flatpacks, $T_{BC}$ was calculated from the measured value of $T_{TC}$ by means of (2). The data points for which $T_{BC}$ was deduced from $T_{TC}$ are flagged in Fig. 2. The flagged and unflagged symbols are seen to agree closely with each other.

The thermal resistance is seen to be a linear function of gap. A least-squares curve fit of the data was made. Separate fits were made for the filled-gap and unfilled-gap data. Six different functions (including linear, exponential, power, and hyperbolic functions) were tried. For both the filled gap and unfilled-gap data, the linear function had the highest coefficient of determination and therefore was the best fit to the data. The best-fit least-squares equations were as follows:

$$\theta = 29.7 + 0.7g \text{ (filled gaps)}$$

$$\theta = 46.4 + 1.1g \text{ (unfilled gaps)}$$

where $\theta$ is in $^\circ$C/W and $g$ is in mils. The coefficient of determination was 0.85 for the filled-gap formula and 0.80 for the unfilled-gap formula. The best-fit least-squares functions for the PWB 1013 data taken alone were the same as for the combined PWB's 1013 and 4019 data. This indicates that the data were repeatable and that two PWB's provided sufficient data for the purposes of this test.

The filler is seen to produce a significant beneficial reduction in the flatpack mounting thermal resistance. The slopes of the best-fit straight lines for the filled-gap and unfilled-gap data were nearly equal to each other, but the filled-gap intercept was nearly 17$^\circ$C/W lower than the unfilled-gap intercept. The filled-gap and unfilled-gap data might be expected to coincide at $g = 0$. As was mentioned previously, however, at $g = 0$ there is a 4-mil-thick layer of air or adhesive between the circuit board and those portions of the flatpack case under which there are no thermal vias.

The beneficial effect of the filler can be seen in a different way in Fig. 3, in which the data are plotted as $\theta_{\text{filled gap}}$ versus $\theta_{\text{unfilled gap}}$. Each data point represents an IC whose thermal resistance was measured before and after applying the adhesive. If the filler had no effect on $\theta$, all the data points would lie on the 45$^\circ$ line shown on the graph. In fact, all the data points fall below the 45$^\circ$ line, which indicates the beneficial reduction in $\theta$ produced by the filler.

**Correlation of Analytical and Experimental Results**

A simplified semiempirical analysis was developed to compare with these experimental results. The temperature
difference between the bottom center of the flatpack case and the cold plate can be written as

\[ T_{BC} - T_{CP} = (T_{BC} - T_{avg}) + (T_{avg} - T_{PWB}) + (T_{PWB} - T_{CP}) \]  

(6)

where \( T_{avg} \) = average temperature of the bottom of the flatpack case. The average temperature can be roughly approximated by

\[ T_{avg} = \frac{(T_{BC} + T_{BE})}{2} \]  

(7)

where \( T_{BE} \) = temperature of the bottom edge (or corner) of the flatpack. Substituting (7) into (6) and dividing by the IC power dissipation yielded

\[ \theta = \frac{T_{BC} - T_{CP}}{P} = \frac{(1/2) \left( T_{BC} - T_{BE} \right)}{P} + \frac{(T_{avg} - T_{PWB})}{P} + \frac{(T_{PWB} - T_{CP})}{P}. \]  

(8)

A formula was derived for each term in (8), making use of the present test data. Because the heat-transfer mechanisms for the filled gaps differ somewhat from those for the unfilled gaps, they were considered separately.

For the filled gaps, the aforementioned test data indicated that \( T_{BE} \approx T_{TC} \), so that the first term was given by (3a). The second term, the thermal resistance of the filler, was given by

\[ (T_{avg} - T_{PWB})/P = g/(k_F A). \]  

(9)

The filler thermal conductivity \( k_F \) had the value \( k_F = 0.1 \text{ Btu/} \text{(h-ft-}^\circ\text{F)} = 0.172 \text{ W/(}^\circ\text{C-m}). The filler cross-sectional area equaled the case area (on the basis of tests that show that the adhesive fills the gap completely), which had the value 0.223 \text{ in}^2 = 1.44 \times 10^{-4} \text{ m}^2. Thus the second term was written as

\[ (T_{avg} - T_{PWB})/P = 1.0 \, g \]  

(10)

where \( (T_{avg} - T_{PWB})/P \) is in \( ^\circ\text{C}/\text{W} \) and \( g \) is in mils. The last term was obtained from the empirical correlation in (3a). Substituting (2a), (3a), and (10) into (8) yielded

\[ \theta = 27.5 + 1.0 \, g \, \text{(predicted)} \]  

(11)

where \( \theta \) is in \( ^\circ\text{C}/\text{W} \) and \( g \) is in mils.

Equation (11), which is plotted in Fig. 2, agreed very closely with the best-fit least-squares curve fit to the test data in the range of practical interest (\( g \ll 10 \) mils). For the larger gaps (only of academic interest), (11) overestimated \( \theta \), possibly because the relatively thick filler layer became sufficiently resistive to heat flow that other heat-transfer paths became significant. In particular, conduction through the flatpack leads became significant at the larger gaps.

To quantify the effect of lead conduction, an approximate formula was derived. Conduction occurred along the L-shaped path shown in Fig. 1, and the conduction length \( L \) was

\[ L = W + (t/2) + g. \]  

(12)

For the 54S181 IC flatpack tested, we measured \( W = 59 \) mils. The average flatpack thickness was measured to be 72 mils, so that \( t/2 = 36 \) mils. We thus obtained

\[ L = 95 \, \text{mils} + g. \]  

(13)

The leads were 5.5 \times 17 mils in cross section and were made of Kovar, whose thermal conductivity was 9.5 \text{ Btu/(h-ft-}^\circ\text{F)} = 16.4 \text{ W/(}^\circ\text{C-m}). The thermal resistance of the 24 leads in parallel was then given by

\[ \theta_{LC} = 101.8 + 1.1 \, g, \]  

(14)

where \( \theta_{LC} \) is in \( ^\circ\text{C}/\text{W} \) and \( g \) is in mils. The temperatures at the hot and cold ends of the leads were not known precisely. It was assumed, for simplicity, that the hot end was at the average temperature \( T_{avg} \) of the bottom of the flatpack case and that the cold end was at the temperature of the PWB. The thermal resistance \( \theta_{gap} \) of the gap was then the result of filler conduction and lead conduction in parallel:

\[ 1/\theta_{gap} = 1/\theta_{FC} + 1/\theta_{LC} + 1/\theta_{rad}. \]  

(15)

Equation (15), which is plotted in Fig. 2, agreed very closely with the best-fit least-squares curve fit over the entire gap range tested. This indicated that the combined effects of conduction through the filler and through the leads explained the experimental results when the measured PWB thermal resistance and the observed temperature gradient around the case were accounted for.

For the unfilled gaps, conduction through the gap was not the only significant heat-transfer mode. Because air is a relatively poor conductor (the thermal conductivity of the filler is more than 6 times as high as that of air), conduction through the flatpack leads and radiation between the bottom of the flatpack case and the PWB were significant, especially at the larger gaps. If one begins with (8), the procedure is the same as for the filled gaps. The first term was given by (3b). The second term was the gap thermal resistance, which was the result of air conduction, lead conduction, and radiation in parallel:

\[ 1/\theta_{gap} = 1/\theta_{AC} + 1/\theta_{LC} + 1/\theta_{rad}. \]  

(16)
The air conduction was calculated in the same way as the filler conduction and was given by

\[ \theta_{AC} = 6.6g \]  

(17)

where \( \theta_{AC} \) is in °C/W and \( g \) is in mils. The lead conduction was given by (14). Because \( \theta_{rad} \) depended on the case and PWB temperatures, it could not be computed \textit{a priori}. Instead a two-step process was employed to calculate \( \theta_{rad} \). First \( \theta_{gap} \) was calculated, neglecting radiation. Assuming a cold plate temperature of 71°C (344 K) and an IC dissipation of 0.5 W, the temperatures \( T_{avg} \) and \( T_{PWB} \) were computed. The radiative heat loss then was computed by means of a simplified model. Assuming the case and PWB emissivities to be 0.85 and the shape factor to be unity, the radiative heat flux \( P_{rad} \), which was predominantly between the bottom of the flatpack case and the PWB, was given approximately by

\[ P_{rad} = 0.012 \cdot (\alpha T_{avg}^4 - \alpha T_{PWB}^4) \]  

(18)

where \( P_{rad} \) is in W and \( \alpha T \) is in W/m². The thermal resistance to radiation then was given by

\[ \theta_{rad} = \frac{(T_{avg} - T_{PWB})}{P_{rad}}. \]  

(19)

The last term was given by (3b). Thus

\[ \theta = 25.0 + \frac{1}{6.6g} + \frac{1}{101.8 + 1.1g} + \frac{1}{\theta_{rad}} \]  

(20)

where \( \theta \) is in °C/W and \( g \) is in mils. Equation (20) is plotted in Fig. 2, and the contributions of air conduction alone and of air conduction and lead conduction in parallel also are shown. The agreement with the best-fit least-squares curve fit was only fair. The formula agreed fairly closely with the test data at the larger gaps but severely underestimated \( \theta \) at the small gaps (<10 mils) of practical interest. This indicated that the heat-transfer phenomena associated with an unfilled air gap were not completely explained by the present analysis.

Application of Test Results

The present tests were conducted under thermal conditions which simulate those experienced under actual operating conditions in an aircraft, but they did not give the desired final results, i.e., the IC junction temperatures when operating in an air-cooled module.

These desired final results were calculated based on the present test results, results of other thermal tests (to determine the junction-to-case thermal resistance \( \theta_{jc} \)), and thermal analyses of the digital module finstock. The results are given in Fig. 4, which is based on the following assumptions:

- The module is operated with a 71°C (344 K) exhaust.
- The module aluminum skin temperature is 14°C higher than the local cooling air temperature. This temperature rise was calculated for a high dissipation digital module.
- The IC dissipates 0.630 W, which is the commonly used value for the highest typical dissipation for IC's used in these digital modules. However, it should be noted that the 545181 IC's used in these tests, which are considered to be among the highest dissipation IC's used in the digital modules, had a measured dissipation of 0.5 W typical. Therefore, there is a degree of conservatism in using a 0.630-W dissipation in preparation of Fig. 4.

- The thermal resistance between the module skin and the bottom center of the IC case is in accordance with (5).
- The thermal resistance \( \theta_{jc} \) from the bottom center of the IC case to the junction is 11°C/W. This is the measured thermal resistance for high dissipation IC's used in the digital modules. Note that this thermal resistance is from the bottom center of the case (the case hot spot) to the junction, and is therefore lower than the more commonly used thermal resistance from the top of the IC case to the junction.

Again referring to Fig. 4, the effectiveness of the filler is again immediately apparent, the junction temperatures being about 12°C lower with the filler. The effect of the gap size is not nearly as pronounced as the effect of the filler; an increase in a filled gap from the thermally preferred 0 mils to the maximum anticipated production gap of 5 mils causes an increase in junction temperature of 3°C. It must be remembered that, for the filler to be effective, it must be replaced when a flatpack is replaced.

CONCLUSION

The following conclusions are drawn from these test results.

1) The filler used in the gap is quite effective in lowering the IC junction temperature (Figs. 3 and 4). A high dissipation (0.630 W) flatpack located near the exhaust of a digital module operated with a 71°C (344 K) exhaust has a junction temperature of 112°C (385 K) and 123°C (396 K), respectively, with a filled and unfilled 2-mil gap.

2) The thermal effect of the gap size is not nearly as pronounced as the effect of the filler (Fig. 2). An increase in a filled gap from the thermally preferred 0 mils to the maximum anticipated production gap of 5 mils causes an increase in junction temperature of 3°C (Fig. 4).
3) For both filled and unfilled gaps, the combined thermal resistance of the gap and the PWB is a linear function of the gap, and is given by (5) and Fig. 2. The present semiempirical analysis explains the experimental results for the case of the filled gap, but not for the case of an unfilled gap, possibly due to threedimensional heat transfer.

4) There is a significant temperature gradient around the flatpack case. The thermal resistance from the top center of the case to the bottom center of the case is 23.2°C/W for a filled gap and 29.2°C/W for an unfilled gap (see (2)). However, the thermal resistance from the top center to the bottom edge (or corner) is small, with an average value of 1.7 to 1.8°C/W, which results in a temperature difference of only 1°C.

5) Lead conduction can be significant with very large unfilled gaps, but it is not significant with moderate size filled gaps (Fig. 2).

6) The gaps measured with the dial indicator method are a few mils smaller than those measured by sectioning. However, because the dial indicator method is nondestructive and because there is a relatively large variation in the gap across the flatpack, the dial indicator technique is satisfactory for measuring the gap in many applications.

ACKNOWLEDGMENT

J. E. James performed most of the tests reported herein. A. M. Schwider developed the adhesive used in these tests.

Generalized Computations of the Gray Body Shape Factor for Thermal Radiation from a Rectangular U-Channel

GORDON N. ELLISON

Abstract—Gray body shape factors are computed for radiation exchange between the interior of rectangular fin structures and a nonreflecting ambient. The shape factors are derived from an equivalent thermal circuit using emissivity-dependent resistance elements between each black body potential and corresponding radiosity node. Geometric-shape-factor-dependent resistance elements connect interacting radiosities. Several curves are plotted to aid the heat sink designer to assess the radiative heat transfer for a variety of heat sink dimensions and emissivities. These results show that gross errors exist in some of the previously published data and prediction methods in common usage throughout the electronics industry.

INTRODUCTION

EXTRUDED aluminum heat sinks are frequently used to reduce the operating temperature of electronic components. In many applications, radiation heat transfer from the sink may be sufficient to substantially increase the component functional lifetime.

A typical heat sink (Fig. 1) consists of a set of rectangular fins made by an aluminum extrusion process. Such fins clearly have one purpose: the enhancement of the total heat sink area. Unfortunately, other factors that reduce the overall performance of the heat sink often accompany the added surface area. In the case of radiation heat transfer, each fin obstructs the view that both the adjacent fins and supporting base have of the ambient to which the radiation heat is exchanged. This paper addresses this shielding effect.

Of particular concern to this writer is that many, if not most, engineers who package electronic equipment are not cognizant of the gross errors in some of the radiation-shielding literature. For example, a common reference [1] contains a set of incorrect shielding factor curves. Also, a recent conference presentation [2] promoted a simple approximation for use when \( L/S \) is three or greater. Used as recommended, this method causes incorrect estimates.

The correct procedure for computing radiation from extruded heat sinks was indicated several years ago [3]. The methodology used was correct, but probably appeared sufficiently complex to discourage most designers. Furthermore, a single specific geometry was used to illustrate the physics of the problem; generally usable guidelines were not provided.

The following paragraphs describe the theoretical technique as well as several sets of graphical results that may be used as an aid to predicting adjacent fin shielding of radiative heat transfer. In addition, several comparisons between the author’s results and those of [1], [2] are made. Accompanying convective heat transfer may be computed by following the procedure outlined in [4].

THEORETICAL BASIS

The analysis herein assumes that the heat sink materials may be classified as gray, diffusely reflecting, opaque surfaces with the fins and base at a uniform temperature.

The objective is to obtain an expression for the gray body shape factor \( F \) for the interior of a complete U-channel section.